Fisheries and Oceans Canada
Science

Pêches et Océans Canada
Sciences

CSAS

Canadian Science Advisory Secretariat

SCCS

Secrétariat canadien de consultation scientifique

Research Document 2012/142

Maritimes Region

Document de recherche 2012/142

Région de Maritimes

Recovery Potential Assessment for Southern Upland Atlantic Salmon: Population Dynamics and Viability

Évaluation du potentiel de rétablissement du saumon de l'Atlantique des hautes terres du Sud : Dynamique et viabilité des populations

A.J.F. Gibson, and H.D. Bowlby

Department of Fisheries and Oceans
Science Branch, Maritimes Region
P.O. Box 1006, Dartmouth, N.S.
Canada, B2Y 4A2

This series documents the scientific basis for the evaluation of aquatic resources and ecosystems in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

Research documents are produced in the official language in which they are provided to the Secretariat.

This document is available on the Internet at:

La présente série documente les fondements scientifiques des évaluations des ressources et des écosystèmes aquatiques du Canada. Elle traite des problèmes courants selon les échéanciers dictés. Les documents qu'elle contient ne doivent pas être considérés comme des énoncés définitifs sur les sujets traités, mais plutôt comme des rapports d'étape sur les études en cours.

Les documents de recherche sont publiés dans la langue officielle utilisée dans le manuscrit envoyé au Secrétariat.

Ce document est disponible sur l'Internet à:

www.dfo-mpo.gc.ca/csas-sccs

ISSN 1499-3848 (Printed / Imprimé)
ISSN 1919-5044 (Online / En ligne)
© Her Majesty the Queen in Right of Canada, 2013
© Sa Majesté la Reine du Chef du Canada, 2013

Canadä

TABLE OF CONTENTS

Abstract iii

Résumé iv

1. Introduction 1

2. Information About Life History (TOR 3) 2
    2.1 Life Cycle of Southern Upland Atlantic Salmon 2
    2.2 Estimation of Life History Parameters 3
    2.3 Survival of Emigrating Smolts and Kelts in Rivers and Estuaries 6
    2.4 Mortality of Adult Salmon Between Spawning Events 7
    2.5 Population Dynamics: Past and Present 7

3. Mortality Associated With Recreational Fishing and Acidification (TOR 9, in part) 10
    3.1 Population Level Effects of Recreational Fishing 10
    3.2 Mortality Associated with Acidification 12

4. Population Viability Analysis using Present Life History Parameters (TORs 20 and 22) 12
    4.1 Population Viability in the Past and at Present 14
    4.2 Effects of Extreme Environmental Events 15

5. Population Viability Analysis of Recovery Scenarios (TORs 21 and 22) 16
    5.1 Effect of Time (Starting Population Size) 17
    5.2 Sensitivity to the Quasi-Extinction Threshold 17

6. Discussion, Uncertanties and Conclusions 17

7. Acknowledgments 21

8. References 21

9. Tables 28

10. Figures 37

11. Appendices 70

Correct citation for this publication:

Gibson, A.J.F., and Bowlby, H.D. 2013. Recovery Potential Assessment for Southern Upland Atlantic Salmon: Population Dynamics and Viability. DFO Can. Sci. Advis. Sec. Res. Doc. 2012/142. iv + 129 p.

ABSTRACT

The purpose of this research document is to provide information about the population dynamics and viability of Southern Upland Atlantic salmon in support of recovery planning for this designatable unit. It covers the topics required for the Recovery Potential Assessment for Southern Upland Atlantic salmon relating to estimation of age- and stage-specific life history parameters (mortality rates and stage transition probabilities), the past and present population dynamics and viability of these populations, and scenario analyses to help identify and prioritize among recovery actions.

Analyses are presented for the LaHave River (above Morgans Falls) and the St. Mary's River (West Branch) salmon populations. Life history parameter estimates were obtained by fitting a life history model to population-specific data including annual estimates of juvenile densities, egg depositions, the number and age composition of emigrating smolts and the numbers of returning adults. The resulting estimates of age- and stage-specific mortality rates, as well as age-specific probabilities of undergoing smoltification and of maturing, were used to estimate smolt abundance and smolt-to-adult return rates in the 1980's, a time when populations were considered viable, and in the 2000's, when populations are not. The results indicate that at-sea survival has decreased by a factor of about two to three between these time periods, but remains about 10 times higher than current survival for inner Bay of Fundy Atlantic salmon. Maximum lifetime reproductive rates decreased from an average of 3.59 in the 1980's to 0.84 in the 2000's for the LaHave population, and from 4.44 to 1.02 over the same period for the St. Mary's population. These populations, two of the larger, more productive populations remaining in the Southern Upland, are expected to extirpate in the absence of human intervention or a change in survival rates for some other reason.

Population viability analyses indicate that relatively small increases in either freshwater productivity or at-sea survival are expected to markedly decrease extinction probabilities, although larger changes in at-sea survival will be required to restore populations to levels above their conservation requirements. In contrast with inner Bay of Fundy salmon populations, for which at-sea survival is so low that recovery actions in fresh water are expected to have little effect on overall viability, recovery actions focused on improving freshwater productivity are expected to increase population viability for Southern Upland Atlantic salmon. The analyses indicate that the loss of past resiliency to extreme environmental events is contributing to the high risk of extinction. Recreational fisheries have reduced productivity in the past, although their overall contribution to the abundance declines is thought to be small given the extent to which population dynamics have changed. Conditional on model assumptions, their impact in the 2000's is thought to be negligible. Research on mortality of adults between spawning events, of smolts and kelts in estuaries, and as a result of acidification is summarized in the document. A sensitivity analysis about the effect of starting population size on population viability highlights the risks associated with delaying recovery actions: recovery is expected to become more difficult if abundance continues to decline, as is expected for these populations with the continued passage of time.

RÉSUMÉ

Le présent document de recherche a pour objet de fournir des renseignements à propos de la dynamique et de la viabilité des populations du saumon de l'Atlantique des hautes terres du Sud à l'appui de la planification du rétablissement de cette unité désignable. Il traite des sujets requis pour l'évaluation du potentiel de rétablissement du saumon de l'Atlantique des hautes terres du Sud relatifs à l'estimation des paramètres du cycle biologique propres à l'âge et au stade (les taux de mortalité et les probabilités de transition de stades), la dynamique des populations passées et présentes et la viabilité de celles-ci, et aux analyses de scénarios afin d'aider à définir des mesures de rétablissement et à établir des priorités entres elles.

Des analyses sont présentées pour les populations de saumon de la rivière LaHave (située au-dessus des chutes Morgan) et de la rivière St. Mary's (bras ouest). Les estimations des paramètres du cycle biologique ont été obtenues en intégrant un modèle de cycle biologique aux données d'une population précise, notamment les estimations annuelles des densités de juvéniles, les pontes, le nombre et la composition selon l'âge des saumoneaux qui émigrent et le nombre d'adultes qui reviennent. Les estimations des taux de mortalité propres à l'âge et au stade, ainsi que des probabilités propres à l'âge en cours de smoltification et de maturité, étaient utilisées pour estimer l'abondance des saumoneaux et les taux de montaison des saumoneaux par rapport aux adultes dans les années 1980, lorsque les populations étaient considérées comme viables, et dans les années 2000, lorsqu'elles ne l'étaient pas. Les résultats montrent que le taux de survie en mer a diminué d'un facteur d'environ de deux à trois entre ces périodes, mais il reste environ dix fois plus élevé que le taux de survie actuel pour le saumon de l'Atlantique de l'intérieur de la baie de Fundy. Les taux de reproduction maximaux pendant la durée de vie ont diminué de la moyenne de 3,59 dans les années 1980 à 0,84 dans les années 2000 pour la population de la rivière LaHave, et d'une moyenne de 4,44 à 1,02 pour la même période pour la population de la rivière St. Mary's. On s'attend à ce que ces populations, les deux populations les plus grandes et les plus productives restantes des hautes terres du Sud, disparaissent en l'absence d'une intervention humaine ou d'un changement dans les taux de survie pour une autre raison.

Selon des analyses de viabilité démographiques, des augmentations relativement faibles de la productivité en eau douce ou de la survie en mer devraient permettre de grandement réduire les probabilités de disparition, même si des changements plus importants sur le plan de survie en mer seront requis afin de rétablir les populations à des niveaux supérieurs à ceux qui sont requis pour leur conservation. Contrairement aux populations de saumon à l'intérieur de la baie de Fundy, dont la survie en mer est tellement faible que des mesures de rétablissement en eau douce auront probablement peu d'effets sur la viabilité globale, les mesures de rétablissement axées sur l'amélioration de la productivité en eau douce devraient augmenter la viabilité démographique du saumon de l'Atlantique des hautes terres du Sud. Les analyses révèlent que la perte de la résilience du passé à l'égard des phénomènes environnementaux extrêmes place l'espèce face à un risque élevé de disparition. Les pêches récréatives ont réduit la productivité par le passé, bien qu'on estime que leur contribution générale de la baisse de l'abondance soit minime étant donné la mesure dans laquelle la dynamique des populations a changé. En fonction des hypothèses du modèle, on estime que leurs répercussions sont négligeables dans les années 2000. La recherche de la mortalité des adultes entre les périodes de frai, des saumoneaux et des charognards dans les estuaires, et par suite de l'acidification est résumée dans le document. Une analyse de sensibilité des effets de la taille de départ d'une population sur la viabilité démographique met en évidence les risques associés au retardement des mesures de rétablissement; le rétablissement est susceptible de devenir plus difficile si l'abondance continue à diminuer, comme on le prévoit pour ces populations.

1. INTRODUCTION

The Southern Upland Designatable Unit of Atlantic Salmon (*Salmo salar*) occupies rivers in a region of Nova Scotia extending from the northeastern mainland, approximately 45° 39' N, 61° 25' W, southward and into the Bay of Fundy to Cape Split, approximately 45° 20' N, 64° 30' W, (COSEWIC 2010). This region includes all rivers south of the Canso Causeway on both the Eastern Shore and South Shore of Nova Scotia draining into the Atlantic Ocean (Figure 1), as well as Nova Scotia rivers draining into the Bay of Fundy south of Cape Split. Historically, it has been divided into three Salmon Fishing Areas (SFAs) for management and assessment purposes: SFA 20 (Eastern Shore), SFA 21 (Southwest Nova Scotia), and part of SFA 22 (Bay of Fundy rivers inland of the Annapolis River). Within the region, there are at least 72 rivers considered to contain, or historically have contained Atlantic salmon, although it is likely salmon would also have used the smaller coastal or un-assessed rivers in the region.

The Southern Upland Designatable Unit of Atlantic salmon was designated as endangered by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC 2010). To aid in consultative processes following the designation, and to serve as a basis for recovery planning, information about Southern Upland Atlantic salmon populations has been compiled into four research documents in support of the Recovery Potential Assessment (RPA) for this Designatable Unit, addressing the 22 Terms of Reference (TORs) developed to guide the process.

In this research document, information has been compiled about the population dynamics of Southern Upland Atlantic salmon, and new analyses are presented about: (1) life history parameters such as stage-specific total and natural mortality rates, and stage transition probabilities; (2) the past and present population dynamics of Southern Upland Atlantic salmon, (3) population viability; and (4) scenario analyses to identify and prioritize among recovery actions. Two of the other documents cover: (1) information related to abundance, trends, trajectories and recovery targets for Southern Upland Atlantic salmon populations (Bowlby et al. 2013a); and (2) functional descriptions of habitat, spatial extent of areas having these properties, threats to habitat and populations, and potential mitigation or remediation of these threats (Bowlby et al. 2013b). A fourth document summarizes information about genetic structuring within salmon populations in the Southern Upland (O'Reilly et al. 2012).

Specifically, the following TORs are addressed in this document:

TOR 3: Estimate, to the extent that information allows, the current or recent life-history parameters (total mortality, natural mortality, fecundity, maturity, recruitment, etc.) or reasonable surrogates; and associated uncertainties for all parameters.

TOR 12: (in part). Quantify to the extent possible the magnitude of each major potential source of mortality identified in the COSEWIC Status Report (COSEWIC 2010), information from DFO sectors, and other sources including:

- Poor marine survival,
- Changes in climate,
- Fishing (bycatch, subsistence, recreational, and illegal),
- Dams and obstructions in freshwater,
- Agriculture, forestry,
- Urbanization,
- Acidification,
- Hatcheries,

- Aquaculture, and
- Invasive species.

TOR 19: Estimate, to the extent possible, the expected impact on abundance and distribution objectives from identified mitigation measures (Step 15), alternatives (Step 16), or recovery activities (Steps 17 and 18).

TOR 20: Given current dynamics parameters and associated uncertainties, project expected population trajectories over three generations (or other biologically reasonable time), and trajectories over time to the recovery objectives, using DFO guidelines on long-term projections (Shelton et al. 2007).

TOR 21: Given alternative mortality rates and productivities associated with specific scenarios identified in Step 17, project expected population trajectory over three generations (or other biologically reasonable time), and to the time of reaching recovery objectives.

TOR 22: Assess the probability that the recovery objectives can be achieved under current rates of population dynamics parameters, and how that probability would vary with different mortality (especially lower) and productivity (especially higher) parameters.

2. INFORMATION ABOUT LIFE HISTORY (TOR 3)

Within the region occupied by Southern Upland Atlantic salmon, there are at least 72 rivers considered to contain, or historically have contained Atlantic salmon, although it is likely salmon would have used the smaller coastal or un-assessed rivers as well (see Bowlby et al. 2013b, Section 2.1). Although there is some variability in life history characteristics, the life cycle of Atlantic salmon is relatively similar among populations throughout the region. In this section, information is provided about the life cycle of Atlantic salmon (Section 2.1) and the life history parameter values for the LaHave River (above Morgans Falls) and St. Mary's River (West Branch) populations are derived using a statistical, life history-based population model (Section 2.2). Recent research about the survival of smolts and post-smolts in rivers and estuaries (Section 2.3) and survival of adult salmon between spawning events (Section 2.4) is summarized; and an analysis of the population dynamics of populations in this region (that integrates the information in this section to determine how population dynamics have changed from the 1980's to present) is presented (Section 2.5).

2.1 LIFE CYCLE OF SOUTHERN UPLAND ATLANTIC SALMON

Southern Upland Atlantic salmon are anadromous fish, meaning that while they are obligated to reproduce in fresh water, most spend part of their lives in the ocean to feed and grow. They are iterparous, meaning that they can spawn several times before they die. After spawning for the first time, some individuals may spawn again in consecutive years, while others may spawn in alternate years and others may switch between alternate and consecutive repeat spawning. Spawning typically occurs in November. After spawning, adults (known as "kelts") may return to the sea or may remain in fresh water until the following spring. Although the proportion of kelts remaining in fresh water is not well studied, a recent (2010/11) acoustic tagging study on the St. Mary's River indicates that the proportion of salmon over-wintering in fresh water is likely very high (Gibson and Halfyard, unpublished data).

Eggs are deposited in nests (referred to as "redds") excavated in the gravel substrate. Hatching begins in April and the yolk-sac larvae (known as “alevins”), remain in the gravel until May or June. After emergence from the gravel, the young (now called “fry”) begin feeding. As they grow, their behaviour changes and they tend to be found in different places in the river. By autumn, they are referred to as “parr”. Parr in Southern Upland rivers typically remain in fresh water for two to four years, although as described in Section 2.3, most leave the rivers at age-2 or age-3. Prior to leaving the river, parr undergo physical changes that allow them to survive in the ocean. These juvenile salmon are now referred to as “smolt” and will migrate to the sea during late April, May and early June. Timing of the smolt run varies somewhat with environmental conditions. Some male parr become sexually mature at a small size while still in the river (these are called “precocious parr”). Within Southern Upland populations, salmon mature after either one or two winters at sea (called “one sea-winter salmon” or 1SW, “two sea-winter salmon” or 2SW, respectively), although historically a small proportion also matured after three winters at sea (called “three sea-winter salmon” or 3SW). The proportion of salmon maturing after a given number of winters at sea is highly variable among populations. For example, in the West Branch of the St. Mary’s River, the majority of salmon mature after one winter at sea, whereas in the East Branch of the river, there is a higher proportion of salmon that mature after two winters at sea. Three sea-winter salmon are now very rare or absent from most populations in the Southern Upland. Adult run timing is variable. In many years, the majority of salmon return to the rivers during late spring or early summer whereas, depending on both oceanic and freshwater environmental conditions, in other years the majority may return during the fall. The terms “small salmon” and “large salmon” are used at times. Small salmon are <63 cm fork length and are virtually all 1SW salmon. Large salmon are ≥63 cm fork length, and include 2SW salmon, 3SW salmon, as well as repeat spawning salmon (“multi-sea-winter” or MSW). A very small component of 1SW salmon may be greater than 63 cm fork length, but these are rare in the Southern Upland.

2.2 ESTIMATION OF LIFE HISTORY PARAMETERS

Life history parameter estimates were derived using a statistical, life history-based population dynamics model developed by Gibson et al. (2008c, 2009b). The model, described in Appendix 1, follows the general theory developed by Fournier and Archibald (1982) and Deriso et al. (1985) for statistical catch-at-age models for stock assessment that allows auxiliary data to be incorporated for model fitting. This approach was adapted to use multiple indices (auxiliary data) to derive estimates of the age- and stage-specific abundances and survival rates required to analyze the dynamics of these populations. This information is then used to determine how recovery actions may be expected to change population size and viability.

The population dynamics model consists of two parts: a freshwater production model that provides estimates of the expected smolt production as a function of egg deposition; and an egg-per-smolt (EPS) model that provides estimates of the rate at which smolts produce eggs throughout their lives. These components are combined via an equilibrium analysis that provides estimates of the abundance at which the population would stabilize if the input parameters remained unchanged. This combined model is then used to evaluate how equilibrium population size has changed through time, as well as how the population would be expected to change in response to changes in carrying capacity, survival, or life stage transition probabilities, as described in Section 2.5.

There are two Atlantic salmon populations in the Southern Upland Designatable Unit with sufficient data for estimating values for life history parameters (i.e. with enough data that the above modeling approach can be used). These are the LaHave River (above Morgans Falls) population and the population in the St. Mary’s River (West Branch). Model equations, symbolism and statistical considerations are described in Appendix 1, and the population specific details of the modelling, model diagnostics and sensitivity analyses are provided in Appendix 2 for the LaHave population and in Appendix 3 for the St. Mary's population. The results of the analyses are summarized in the text below. For both populations, the model is set up using data from 1974 to 2010.

LaHave River (above Morgans Falls)

The model results summarized in this section are for the base model run that consisted of using standardized electrofishing time series for juvenile density estimates derived using only sites that had been fished more than two times and partitioned by age class using the age composition derived from the length-frequency data; as well as the adult river ages to estimate the smolt numbers-at-age. Sensitivity analyses are provided in Appendix 2 and a comparison of the various model runs is provided in Appendix 2: Table A2.6.

Parameter estimates obtained for the LaHave population are biologically plausible (e.g. mortality estimates between 0 and 1) and the standard errors of the estimates were not large relative to the means indicating reasonable model fits (Table 2.2.1, Appendix 2: Table A2.6). Mortality from the egg to the fry stages (at the time of the electrofishing surveys in mid-summer) was estimated to be 0.88, meaning 88% of individuals die from the time of egg deposition to the time of the survey. The α parameter is the maximum survival from the fry stage to the age-1 parr stage, which occurs at low abundance in the absence of density dependence. The value of 0.72 means that, at most, an average of 72% of fry survive to age-1 (during the time period between the electrofishing surveys in one year and the surveys in the next). The carrying capacity of age-1 parr, R_{asy}, was estimated to be 35.5 parr per 100 m^2. This is the maximum density of age-1 parr that would occur if there were a very large (infinite) number of spawners in the river. Estimation of time varying model parameters (which would represent historical and current dynamics separately, rather than the entire time period considered in the model) was attempted, but was only successful for the smoltification probabilities. The parameter value for j_2 (before 1985) of 0.83 is interpreted to mean that on average, in the 1974 to 1985 time period, 83% of the age-2 parr undergo smoltification in the spring at that age and emigrate from the river. The estimate of the annual mortality rate for parr older than age-1, M_{parr}, for the LaHave population is higher than for the St. Mary's River (West Branch) population (Table 2.2.1). This parameter is the proportion of parr older than age-1 that die annually (i.e. mortality between age-1 and age-2, or between age-2 and age-3) and is assumed to be the same for all age classes in this category.

As described in Appendix 1, these parameter values can be combined to summarize the dynamics of juvenile salmon in freshwater (i.e. to describe survival from egg deposition to smoltification). The analyses indicate that for the 1974 to 1985 time period, the maximum number of smolts produced per egg is 0.017 and that this value decreased to 0.013 in the 1985 to 2010 time period (Table 2.2.1). Similarly, the carrying capacity for smolt decreased from 147,700 to 119,690 for the part of the LaHave River watershed located above Morgans Falls. Again, these values can loosely be interpreted as averages for the two time periods. Similar to the interpretation for parr above, the maximum number of smolts produced per egg occurs at very low abundance in the absence of density dependence and as abundance increases, survival decreases, resulting in a lower number of smolt per egg. The carrying capacity for smolt is the maximum number of smolt that would occur if there were a very large (infinite) number of spawners in the river. The decrease in both of these values suggests that freshwater productivity is lower in more recent years than prior to 1985.

The model is set up to provide estimates of the abundance of salmon at several life stages. In the case of the egg depositions, there are empirical estimates of egg depositions (calculated from adult escapement) and the model is fit to these data. In the case of the LaHave population, the model fits the data well (Figure 2.2.1), but estimated egg depositions for some years in the early 1980's that are higher than the observed values (because high juvenile densities were observed – See Appendix 2). The time series show that the population increased rapidly after the construction of the fishway and again in the mid-1980's coincident with the closure of the commercial salmon fisheries in the region. Smolt abundance estimates from monitoring data are available from 1996 to 2010 (Figure 2.2.2) and the model is fit to these data as well. However, a nice feature of the model is that it can be used to estimate what the smolt abundances would have been over the entire time period (i.e. the predicted values from the model). Based on these estimates, smolt abundance in the 1980's would have been two to five times higher than at present. If these abundance estimates are scaled by amount of habitat in the river, they indicate that smolt production per unit area has decreased from a maximum of nearly 2.5 smolts per 100 m^2 to about 0.6 smolts per 100 m^2 at present (Figure 2.2.3). These values are low relative to those seen in other rivers, but are not necessarily indicative of poor habitat quality. Rather, adult abundance above Morgans Falls was never high enough to fully realize the production potential in the river (See Section 2.5).

Because the model is set up to produce estimates of smolt abundance in the past, and because adult counts are also available, return rates (both to the mouth of the river and to Morgans Falls), can be estimated. This comparison of past and present return rates would not be possible without the model. The observed and estimated return rates of 1SW and 2SW salmon to the river mouth are shown in Figure 2.2.4. Both the 1SW and 2SW return rates show marked increases in the mid-1980's coincident with the closure of the commercial fisheries on Nova Scotia's coast. Return rates generally declined from 1985 to 1995 and have fluctuated without a clear trend since that time.

A summary (mean, minimum and maximum) of the return rate estimates for the 1980's and 2000's is provided in Table 2.2.2. In the 1980's, return rates varied between 2.87% and 17.60% for 1SW salmon and between 0.31% and 1.21% for 2SW salmon. In the 2000's, return rates varied between 2.25% and 4.14% for 1SW salmon and between 0.10% and 0.52% for 2SW salmon. Bayesian posterior probability densities (Figure 2.2.6 and Figure 2.2.7) indicate that the means for the two time periods are reasonably well estimated by the model, and 95% Bayesian credible intervals (an indicator of the probability that the rates are different) do not overlap.

St. Mary's River (West Branch)

The model results summarized in this section are for the base model run that consisted of using the standardized electrofishing time series for juvenile density and past adult abundances calculated using an assumed exploitation rate of 0.3, and fitting the model to all data from 1974 to 2010. Sensitivity analyses are provided in Appendix 3 and a comparison of the various model runs, including past adult abundances derived using other assumed exploitation rates, is provided in Appendix 3: Table A3.7. Parameter estimates are relatively similar (in the sense that they do not alter conclusions about viability) for the different model runs, particularly for the recent time period.

Parameter estimates obtained for the St. Mary's River (West Branch) population are biologically plausible (e.g. mortality estimates between 0 and 1) and the standard errors of the estimates were not large relative to the means indicating reasonable model fits (Table 2.2.1, Appendix 3: Table A3.7). Parameter estimates are interpreted in the same way as those for the LaHave population. The carrying capacity of age-1 parr, R_{asy}, estimated to be 11.76 parr per 100 m^2, is low relative to that estimated for other populations. In a meta-analysis of the timing of density dependence in salmon populations, Gibson (2006) estimated the median carrying capacity for the nine Atlantic salmon populations included in his analysis to be 24.8 parr/100 m^2, although carrying capacity was highly variable with 95% of the probability density falling between 3.8 and 165.9 parr/100 m^2.

The model for the St. Mary's River (West Branch) population was not set up to estimate past and present freshwater dynamics due to the limited amount of data in the earlier years (only the egg time series begins prior to 1990). When the parameter values are combined to summarize the dynamics of juvenile salmon in fresh water, the estimated number of smolts produced per egg is 0.034 and the carrying capacity for smolt is estimated to be 104,120 smolts (Table 2.2.1). These values can loosely be interpreted as average values for the time period (1974 to 2010).

Model fits to the data are reasonably good. In the case of the egg depositions, there are empirical estimates of egg depositions (calculated from adult escapement) and the model is fit to these data. In the case of the St. Mary's population, the perfect fits to the egg data before 1990 (Figure 2.2.1) is a modeling artifact because there are no other data during this time period. The time series shows several years in the 1980's when population is estimated to be above its conservation requirement and the highest egg depositions in the time period occurred immediately after the closure of the commercial fisheries in the early 1980's. Smolt abundance estimates are available from 2005 to 2009 (Figure 2.2.2) and the model is fit to these data as well. As mentioned, a nice feature of the model is that it can be used to estimate what the smolt abundances would have been over the entire time period. Based on these estimates, smolt abundance in the 1980's would have been four to eight times higher than in the late 2000's. If these abundance estimates are scaled by amount of habitat in the river, they indicate that smolt production per unit area has decreased from a maximum of nearly four smolts per 100 m^2 to about one smolt per 100 m^2 at present (Figure 2.2.3). The higher values estimated in the 1980's are reasonably high relative to other rivers, but the lower values in the 2000's are not necessarily indicative of poor habitat quality. Rather, low adult abundance in the 2000's is almost certainly limiting freshwater production in the river (See Section 2.5).

As was the case with the LaHave model, return rates (both to the mouth of the river and to the spawning escapement in the fall) can be estimated for the St. Mary's population using the model. The observed and estimated return rates of 1SW and 2SW salmon to the river mouth are shown in Figure 2.2.5. Similar to the LaHave population, return rates show marked increases in the mid-1980's coincident with the closure of the commercial fisheries on Nova Scotia's coast.

A summary (mean, minimum and maximum) of the return rate estimates for the 1980's and 2000's is provided in Table 2.2.2. In the 1980's, return rates varied between 1.17% and 5.52% for 1SW salmon and between 0.54% and 2.11% for 2SW salmon. In the 2000's, return rates varied between 0.18% and 2.11% for 1SW salmon and between 0.00% and 0.30% for 2SW salmon. Bayesian posterior probability densities (Figure 2.2.6 and Figure 2.2.7) indicate that the means for the two time periods are reasonably well estimated and 95% Bayesian credible intervals (an indicator of the probability that the rates are different) do not overlap.

2.3 SURVIVAL OF EMIGRATING SMOLTS AND KELTS IN RIVERS AND ESTUARIES

Halfyard et al. (2012) studied the survival of emigrating smolts in the LaHave, St. Mary's and Gold rivers in 2010, and in West River (Sheet Harbour) in 2008, 2009 and 2010. Observed survival from release to the head of tide ranged from 71.9% to 100% and survival to the open ocean ranged from 39.4% to 73.5% (Table 2.3.1). The spatial distribution of mortalities within river and year combinations was variable (Figure 2.3.1). Mortality was highest in fresh water in the LaHave, St Mary's and West rivers (2010), but was highest in the inner estuary for the West River in 2008 and 2009, and in the Bay zone for Gold River. Halfyard et al. (2012) used active tracking to try to locate tags from smolts that died. Approximately 86% of all tags could not be found (Figure 2.3.1) and were assumed to have been removed from the water. Predation or scavenging by avian or terrestrial piscivores was thus assumed to have accounted for 75% to 100% of all tag disappearances in the monitored areas. However, detection probabilities during active tracking in fresh water were expected to be quite low in some habitats so it could not be confirmed that the tags had actually been removed.

There are two studies of kelt survival in Southern Upland estuaries. In the St. Mary's River, 24 acoustically tagged kelts were detected leaving the river in the spring of 2011, and all survived to leave the estuary (Gibson and Halfyard, unpublished data). In a study of the survival and behaviour of migrating kelts in freshwater, estuarine, and coastal habitat using LaHave River salmon, 27 of 30 acoustically tagged fish were detected leaving coastal habitat, indicating that survival was at least 90% while migrating through those environments (Hubley et al. 2008).

2.4 MORTALITY OF ADULT SALMON BETWEEN SPAWNING EVENTS

Estimation of annual mortality between repeat spawning events is complicated because there are three parameters to be estimated (mortality in the first year after spawning, mortality in the second year after spawning, and the probability of being a consecutive-year or alternate-year repeat spawner), whereas there are only two observed values (the proportion of consecutive-year and alternate-year repeat spawners). Hubley and Gibson (2011) resolved this problem by developing a hierarchical, Bayesian model that can be used to estimate annual mortality of repeat-spawning Atlantic salmon which distinguishes between mortality rates and the confounding effects of consecutive-year and alternate-year repeat spawning strategies. The model provides annual estimates of two mortality rates: mortality in the 1st year, a time period during which salmon are primarily in fresh water (staging, spawning and over-wintering) followed by a brief period at sea; and mortality in the 2nd year, when salmon are predominantly at sea.

Gibson and Hubley (2011) fit the model to adult repeat-spawning Atlantic salmon data from the LaHave River (above Morgans Falls), using data from the 1978 to 2008 time period. The resulting estimates of mortality in the first year show an increasing trend throughout the time series, whereas mortality in the second year also increased but tended to oscillate (Figure 2.4.1). Decadal comparisons of parameter estimates (Table 2.4.1) indicate that mortality in the first year has continued to trend upward, indicating increasing mortality in freshwater or marine near-shore regions (near-field), whereas average second-year mortality values increased from the 1980's to the 1990's, consistent with a regime shift in the oceanic (far-field) environments. The probability of consecutive spawning varied during the time without any obvious trend in period. Fluctuations in the second-year mortality parameter matched fluctuations in the winter North Atlantic Oscillation Index (Figure 2.4.2), although this relationship was not apparent after 2000, possibly indicating a change in the regulatory mechanism in the later time period (however, low abundance effects cannot be ruled out as a confounding factor in the later time period).

2.5 POPULATION DYNAMICS: PAST AND PRESENT

Human activities may affect some parts of a fish population's life history, such as its average fecundity, survival from one age class or life stage to the next, age-at-maturity or the number of times an individual reproduces. These parameters in turn affect the population's productivity, and one way to assess the effects of a human activity is to evaluate the expected change in productivity that results from changes in life history parameters.

Equilibrium modeling is one approach that can be used to assess impacts of human activities in this way. This kind of analysis begins by splitting the life cycle of salmon into two parts, and for a given set of life history parameters, determining the population size at which the rates in each part of the life cycle are balanced such that the population does not increase or decrease in size. This is the population equilibrium for that specific set of parameter values. By varying the life history parameters in a manner that represents the expected response to a human activity and examining the resulting change in equilibrium population size, the effects of the activity on the population can be evaluated. Equilibrium models are widely used for analyzing population dynamics (Moussalli and Hilborn 1986), for estimating biological reference points for fisheries management (Myers et al. 1994), for providing a basis for the estimation of the long-term consequences of mortality caused by pollution, dams or other human activities (Barnthouse et al. 1988) and for linking fish habitat and fish population dynamics (Hayes et al. 1996).

In the case of Atlantic salmon, a natural split in the life cycle occurs at the smolt stage when fish are migrating to the marine environment. The first part of the model gives freshwater production (the number of smolt produced as a function of egg deposition). The second part is the lifetime EPS relationship, which gives the rate at which smolts are expected to produce eggs during their entire life. This approach is illustrated in Figure 2.5.1. In this example, the commonly used Beverton-Holt function is used to model smolt production in fresh water (Figure 2.5.1a). This model has two parameters: the slope of the function at the origin which gives the maximum rate at which eggs survive to become smolts. This is based on the idea that survival is greatest when population sizes are very low because competition between fish, which can result in reduced growth and increased mortality, is low. The other parameter is the carrying capacity of the river, which is the number of smolts that would be produced if egg deposition was extremely high. Changes in habitat quantity, say as a result of providing fish passage to areas that were previously inaccessible, have the effect of changing carrying capacity. Changes in habitat quality, say as a result of improving or reducing water quality, has the effect of changing the slope at the origin, but may also change carrying capacity as well (Hayes et al. 1996). Although only two parameters are used here, they combine the effects of egg-to-fry survival, fry-to-parr survival, parr-to-smolt survival and age-at-smoltification (Trzcinski et al. 2004).

The lifetime EPS relationship (Figure 2.5.1b) is assumed to be density independent. This is to say that the rate at which smolts produce eggs throughout their lives does not depend on the number of smolts that are produced. This is the equivalent of assuming resource availability in the marine environment is not limiting population growth, and therefore mortality at sea is not density-dependent. In contrast, resource availability in freshwater (see above), which determines carrying capacity, was assumed to limit production of smolt. This paradigm is consistent with most population models for diadromous fish, and is further supported by a recent analysis of the timing of density dependence in Atlantic salmon, which found strong evidence for density dependence in salmon populations within fresh water and little evidence for density dependence in salmon within the marine environment (Gibson 2006). The rate at which smolts produce eggs is calculated based on the survival of juvenile salmon in the marine environment, age-at-maturity, fishing mortality, fecundity, and the number of times a fish spawns throughout its life.

The population equilibrium is derived by finding the abundance at which the production of smolts by eggs equals the reciprocal of the production of eggs by smolts (Figure 2.5.1c); note that graphically this is the equivalent of flipping the axes in Figure 2.5.1b, so that the plots can be overlain. The equilibrium is the population size at which the population will stabilize if all model parameters do not change. Effects of human activities or other changes to population dynamics are evaluated by examining how the equilibrium changes in response to changes in the life history parameters resulting from the activity. In the example shown in Figure 2.5.1c, a decrease in smolt-to-adult survival shifts the equilibrium point to a smaller population size. If smolt-to-adult survival decreases far enough, the equilibrium population size goes to zero and the population will become extinct in the absence of human intervention or a change in one or more of the vital rates. However, an equilibrium population size greater than zero does not necessarily mean that a population is viable, because no allowance is made for random variability in the life history parameters or for catastrophic events.

The mathematics underlying the equilibrium analysis, including the lifetime eggs-per-smolt calculations and the calculations for equilibrium population size, are provided in Appendix 1.

The lifetime EPS models are a useful mechanism for evaluating how the changes in return rates described in Section 2.2, and the changes in repeat spawning dynamics described in Section 2.4, influence a smolt's contribution to subsequent salmon production. The results of these analyses are summarized in Table 2.5.1. For the LaHave population, EPS values ranged between 87 and 489 eggs/smolt in the 1980's and between 29 and 111 eggs/smolt in the 2000's. Similar changes were estimated for the St. Mary's population, although the EPS values were generally lower. Bayesian posterior probability densities for the lifetime EPS estimates of the average values for the 1980's and 2000's time periods (Figure 2.5.2) indicate that the maximum likelihood estimates reasonably match the modes of the posterior densities. The 95% Bayesian credible intervals for the two time periods do not overlap for either population (an indicator of the probability that the rates are different).

The results of the equilibrium analyses are summarized in Table 2.5.2 and Figure 2.5.4 for the LaHave River (above Morgans Falls) and Figure 2.5.5 for the St. Mary's River (West Branch). As mentioned, the equilibrium is the population size at which the population will stabilize if all model parameters do not change. To see how this works, consider Figure 2.5.4, top panel. Start at an egg deposition of 5 million eggs, and use the curved freshwater production line to determine how many smolts would be produced. Then use the average EPS line (the middle dashed line) to determine how many eggs would be produced by that number of smolts. Then, for that number of eggs, determine how many smolts would be produced, and so on. You should rapidly approach the equilibrium (the point where the freshwater production curve intersects the EPS line). Then try the same thing in Figure 2.5.4, bottom panel, starting at 20 million eggs. It should become evident that the equilibrium is an attractor towards which the population moves, and that recovery planning is about shifting the attractor to a place that causes the population to increase in size.

As shown in Figures 2.5.4 and 2.5.5, the equilibrium population size for both populations varied substantially in the 1980's because of changes in the return rates and with the repeat spawning component. However, even at the minimum values observed during that time period, the equilibrium was greater than one. During the 2000's, the mean equilibrium for the LaHave population was zero (Table 2.5.2), indicating that the population will extirpate in the absence of human intervention or another factor that causes a change in the life history parameter values.

The equilibrium population size for the St. May's population is slightly greater than zero, but is low enough that the population is expected to be at high risk of extirpation due to the effects of random environmental variability. Maximum lifetime reproductive rates for the LaHave and St. Mary's populations (Table 2.5.2) have decreased from averages of 3.59 and 4.44 in the 1980's, respectively, to averages of 0.84 and 1.02 during the 2000's. These values mean that during the 2000's, at low abundance and in the absence of density dependence (which further lowers reproductive rates), a salmon in the LaHave River produces on average a total of 0.84 replacement salmon throughout its life. Because this value is less than one (which would indicate that each spawner could replace themselves), the population is not considered viable. In the St. Mary's River, a salmon produces on average a maximum of 1.02 replacement salmon throughout its life, indicating that the population has almost no capacity to rebuild if environmental events such as floods or droughts lower survival at some point in time. Note that the minimum marine survival rates indicate that there are years when the maximum lifetime reproductive rate is less than one, which is why this population is at risk from environmental stochasticity.

3. MORTALITY ASSOCIATED WITH RECREATIONAL FISHING AND ACIDIFICATION (TOR 9, IN PART)

3.1 POPULATION LEVEL EFFECTS OF RECREATIONAL FISHING

Recreational fishing seasons, regulations and practices in the Southern Upland have changed through time from fisheries that were primarily retention fisheries for both large and small salmon, to virtually all hook-and-release fisheries, to closures throughout the Southern Upland Region in 2010.

Hook-and-release recreational fisheries provide an intermediate management strategy between a full retention fishery and fishery closure for populations that are below target levels. Their population-level effects can be evaluated using the equilibrium dynamics models presented in Section 2. The effects are conditional on the life history and dynamics, such as freshwater productivity, survival at-sea and repeat spawning frequency. Catch and release fisheries would be expected to result in populations sizes that are higher than those in a full retention fishery, but lower than those expected to result from fishery closure (Figure 3.1). A similar relationship is expected for the lifetime reproductive rates. As such, they have the potential to slow recovery rates relative to fishery closures, although population growth is expected to be more rapid with a catch and release fishery than a full retention fishery (Figure 3.1).

In this section, the effect of the recreational fishery on the dynamics of salmon in the region is examined using the population dynamics models presented in Section 2 as a basis for the evaluation.

As described in Appendix 2 and 3, a hook-and-release mortality rate of 4% is assumed, consistent with recent salmon stock assessments in the Maritimes Region. DFO (2011) summarized information about hook-and-release mortality:

> "ICES (2009) evaluated the results of studies that estimate the levels of pre-spawning mortality of salmon caught and released by anglers and their implications for stock assessments. In most areas of North America, mortality resulting from catch-and-release angling is incorporated into assessments of spawning escapement and returns (ICES 2010). Highly variable rates of fish mortality associated with a fish being hooked and

> subsequently released have been reported (Dempson *et al.*, 2002; Thorstad *et al.*, 2003). Water temperature is cited as an important factor; angling at low temperatures (i.e., below 17-18°C) generally results in lower mortalities than catch-and-release angling that occurs at higher water temperatures (ICES 2009). ICES (2009) provides a tabular summary of catch-and-release mortality studies on Atlantic salmon, which lists mortality rates and respective water temperatures. The mortality rates associated with catch-and-release angling at water temperatures less than 12°C are predominately $\leq$ 3 %, and five of five studies conducted at temperatures less than 10°C reported no mortality associated with catch-and release. In addition to temperature, fish mortality associated with catch-and-release angling is also believed to be affected by an angler's level of experience; fish mortality is believed to be lower for more experienced anglers than for less experienced anglers. These studies show low direct mortality associated with catch-and release recreational fisheries if conducted at low water temperatures. Although there is information available on the short-term physiological effects of angling, there is little information available about other effects of catch and release salmon fishing (e.g., potential effects on migration, reproduction, habitat impacts, transfer of pathogens, etc.)."

The review in ICES (2009) also indicated that water temperatures above 20°C resulted in much higher estimates of hook-and-release mortality, ranging from 30% to 80%. The results presented in this section are based on the numbers of salmon caught, retained and released in the recreational fishery described in Appendix 2 and Appendix 3 with an assumed hook-and-release mortality rate of 4%. If hook-and-release mortality is higher, then the impact on the population is underestimated, and vice versa.

There is only one population in the Southern Upland with sufficient data to directly evaluate the effects of the recreational fishery, the LaHave River (above Morgans Falls). Even for this population, assumptions need to be made about the proportion of the recreational catch in the LaHave River that are fish destined for above Morgans Falls (see Appendix 2). Results are presented here for the St. Mary's River (West Branch), but this is for the assumed exploitation rate of 0.3 scenario used to estimate abundance in the years prior to 1997. Other assumptions are possible, as summarized in Appendix 3.

As mentioned, the effects of the recreational fisheries are conditional on the life history of populations, and would vary with factors such as freshwater productivity, survival at-sea and repeat spawning frequency. Here, the effects of the recreational fishery on the lifetime egg production per smolt, the equilibrium population size and the maximum lifetime reproductive rates are examined by deriving these values using return rates to the river mouth (described above), and comparing those to similar values derived using return rates to spawning escapement.

The results are shown in Tables 2.2.2, 2.5.1 and 2.5.2. For the LaHave River (above Morgans Falls), in the 1980's when retention fisheries were in effect, the recreational fisheries reduced survival to spawning escapement by up to 31% for 1SW salmon, with lesser effects on 2SW in part due to the timing of the increase in recreational fishing effort and the shift to hook-and-release fisheries for 2SW salmon. This led to a reduction in EPS of up to 25% during the 1980's (Table 2.5.1), leading to a reduction in equilibrium population size of up to 48% (this would be higher than the effect on EPS if fishing mortality is high in two or more sequential years) and reductions in maximum lifetime reproductive rates of up to 23% (Table 2.5.2). With the switch to hook-and-release fisheries, the impact of the fishery on the dynamics of the population is much less (nearly negligible), but this conclusion is conditional on the assumed 4% hook-and-release mortality rate and on the assumption that non-lethal effects of hook-at-release are minor. Similar values are provided for the St. Mary's River (West Branch) salmon population; however, the reader is reminded that the values are conditional on an assumed catch rate for this population in addition to the caveats above. For both populations, the effects are expected to be greater if the fishing season extends into periods with warmer water temperatures. For example, when the analysis for the LaHave River (above Morgans Falls) population is run assuming a 20% hook-and-release mortality value, for the 2000's time period, the minimum values for the egg-production-per-smolt and the maximum lifetime reproductive rate at spawning escapement (after the fishery) are about 8% lower than the values calculated at the river mouth (before the fishery). Additionally, these values should be interpreted in the context of the past impacts of the fisheries on these populations. In the future, any impacts to populations from the recreational fishery would depend on fishing intensity and management regulations with respect to timing of the fishery, as well as the associated mortality rate.

3.2 MORTALITY ASSOCIATED WITH ACIDIFICATION

Many Atlantic salmon populations in the Southern Upland region have been heavily impacted by acidification (Farmer et al. 1980, Farmer 2000, Watt 1987). As discussed in Bowlby et al. (2013b - Section 5.1), low pH can affect the survival of all freshwater stages of Atlantic salmon, with fry being the life stage that is most sensitive to low pH (Johnston et al. 1984, Lacroix 1985, Farmer 2000).

Mortality associated with acidification is relatively well studied, and has been used in multiple models to predict the effects of acidification on the dynamics of salmon populations (e.g. Korman et al. 1994, Gibson et al. 2008c). Korman et al. (1994) developed toxicity functions by life stage and used these to estimate egg-to-smolt mortality rates associated with pH for specific periods (their Table 1). Mortality estimates by life stage from these functions for surface pH values of 4.5 to 5.5 are provided in Table 3.2.1. These rates are in addition to natural mortality and mortality from other causes. The reduction in survival is greatest for fry, consistent with LaCroix (1985) and LaCroix et al. (1985) from which some of the relationships were derived.

Further information on the extent of acidification in rivers in the Southern Upland, as well as evidence from field studies on the effects of low pH and its seasonal characteristics, are provided in Bowlby et al. (2013b - Sections 4.1 and 5.1).

4. POPULATION VIABILITY ANALYSIS USING PRESENT LIFE HISTORY PARAMETERS (TORS 20 AND 22)

The long-term population projections requested in TORs 20, 21 and 22 are carried out using a population viability analysis (PVA). PVAs are used extensively in conservation biology to predict both the risk of extinction for populations and species and to evaluate management strategies to recover at-risk populations. In a PVA, a population dynamics model is used to determine how the probability of persistence is affected by current conditions and future perturbations (Beissinger and McCullough 2002), and models are often used to identify threats to the persistence of a population and to evaluate how future management actions or environmental changes may influence the probabilities of extinction or of achieving recovery goals (Reed et al. 2002). Using simulations of population trajectories, PVA allows one to explore the logical implications of current knowledge and assumptions (Bowlby and Gibson 2011).

Although some authors have cautioned against the use of PVAs because the predictions, typically time to extinction, are almost always quite uncertain (e.g. Taylor 1995; McCarthy et al.

1996; Ludwig 1999), many authors believe that PVAs can be used to assess relative risk (e.g. Akçakaya and Raphael 1998; Beissinger and Westphal 1998; McCarthy et al. 2001). Reed et al. (2002), argue that these relative evaluations are the most appropriate use of PVAs and can be used as a basis for choosing the most effective management strategy from a given set of possibilities (Lindenmayer and Possingham 1996).

Some relatively simple PVA models are possible. For example, the Dennis-type PVA (Dennis et al. 1991) can be used to evaluate extinction risk if the assumption is made that future trends will be similar to past trends, although this type of model is of limited utility for evaluating recovery actions because the underlying biology is not considered. Models which track abundance at multiple life stages are therefore preferred when evaluating population persistence (O'Grady et al. 2004), provided adequate data are available and uncertainties are accounted for (Holt and Peterman 2008, Legault 2005, McCarthy et al. 2001). Because considerable information about the dynamics of Southern Upland Atlantic salmon exists, they are a population assemblage that is well suited for population viability analysis.

With respect to selecting recovery strategies, McCarthy et al. (2003) used a simulation study and found that they were able to identify the better of two management strategies 67–74% of the time using 10 years of data, and 92–93% of the time with 100 years of data. As shown in Section 2, the population dynamics of Southern Upland Atlantic salmon have changed considerably in the last 30 years (as would be true of any species whose conservation status has changed), so very long time series under static conditions simply are not available (as would be true of any species whose conservation status has changed). However, we derived parameter estimates for two 10-year time periods (the 1980's and 2000's; Section 2) when the dynamics of the populations were very different. Comparison of the PVA results from these periods helps to ensure that the conclusions about present population viability are not simply a modeling artifact in the PVA.

The PVA model used here is described in detail in Appendix 4, and is an adaptation of the population dynamics model used to estimate life history parameter values (described in Appendix 1). The model is fully age- and stage- structured and tracks abundance of all life stages and age classes for the duration of the forward projection. As described in Appendix 4, auto-correlated random variability is added at each age class or life stage transition. As the strength of this autocorrelation increases, good years are increasingly likely to be followed by good years (and bad followed by bad).

Additionally, because Atlantic salmon occupy habitats that are periodically subject to extreme conditions (e.g. floods and droughts), the effects of extreme events (which can lead to very high mortality) were included in the model. The life history of Atlantic salmon, which distributes the reproductive effort of a cohort over multiple years, likely evolved in part as a strategy to cope with this kind of variability, and changes in their dynamics can affect the age structure in a population. In this analysis, extreme events affect survival between the egg and the fry life stages, thereby allowing density-dependent compensation to occur which would partially offset some of the mortality. The effect of the extreme events would be greater if it was incorporated after density dependence (i.e. after age-1) in the life cycle.

The frequency and magnitude of extreme environmental events have not been determined for these populations. In most model runs, the probability that an extreme event occurred was set to 0.1 and the effect of the extreme event was assumed to reduce fry abundance by 80%. This means that on average, 10 events reducing the abundance of fry by 80% from the expected value would occur every 100 years. As modeled, a greater or lesser number of extreme events could occur in any simulated population trajectory, and their distribution through time is random (see Appendix 4 for details). The sensitivity of the results to these assumed values was evaluated by running scenarios with no extreme events, as well as scenarios with more extreme environmental events. As shown in Section 2, the population growth rates of Southern Upland Atlantic salmon are currently very low, making it difficult for populations to recover after low survival events. Although the values used to simulate extreme mortality events are assumed, this loss of resiliency is clearly illustrated via this analysis.

Analyses were carried out for both the LaHave River (above Morgans Falls) and the St. Mary's River (West Branch) salmon populations, using both the 1980's ("past") and 2000's ("present") dynamics. Populations are modelled as closed populations, meaning that they are not affected by either immigration or emigration. For each scenario analyzed with the PVA, 2000 population trajectories were simulated and the extinction and recovery probabilities were calculated as the proportion of populations that go extinct by a specified time. For both the past and present scenarios, the population was projected forward from a starting abundance based on the estimated adult population size in 2010. In each case, the numbers of eggs, parr, smolt and adults, as well as their age, sex and previous spawning structure at the start of each simulation were calculated from the adult abundance using the life history parameter values specific to the dynamics being simulated. To evaluate extinction probabilities, a quasi-extinction threshold of 15 females was assumed. This means that annual egg deposition is given a value of zero if the abundance drops below 15 females. A population must be below this value for two consecutive years to be assumed extinct in a given year. However, if the female abundance is higher in the next year, the egg deposition is calculated as per the model. A population can therefore sit on the quasi-extinction threshold for a number of years and can theoretically recover unless there are several sequential years where the female spawner abundance is less than 15. When evaluating recovery probabilities, the conservation requirement was used as the recovery target (see Bowlby et al. 2013a - Section 3.1). The probability of recovery is calculated as the proportion of the simulated populations that are above the recovery target in a given year. Abundance in a population may be above the recovery target for a period of time, but is no longer considered recovered if its abundance subsequently drops to a level below the recovery target.

Abundances for each life stage were projected forward for 100 years even though there is considerable uncertainty about what the dynamics of these populations will be at that time. However, the reason for using these long-term projections is not to estimate what abundance will be at some time, but rather to evaluate longer term viability for each scenario (i.e. does the projection go to zero or not). In other words, the longer term projections are used to determine whether the populations are viable for each combination of life history parameters, random variability and extreme events included in the scenario.

4.1 POPULATION VIABILITY IN THE PAST AND AT PRESENT

Abundance trajectories for the LaHave River (above Morgans Falls) salmon population (Figure 4.1) indicate that, given the present (2000's) population dynamics, this population will extirpate and has zero probability of reaching its recovery target (Table 4.1, Figure 4.2). The probability of extinction (Table 4.1, Figure 4.2) increased rapidly after about 15 years, with 31% of the simulated populations being extinct within 30 years and >95% going extinct within 60 years. None of the 2000 simulated population trajectories met the recovery target within 100 years (Table 4.1). This result is consistent with the maximum lifetime reproductive rate estimate of less than one (indicating that the population should continually decline under current dynamics) and the equilibrium population size of zero (Section 2.5). In contrast, abundance trajectories using the past (1980's) dynamics (Figure 4.1) indicate rapid population growth. None of the simulated population trajectories extirpate within 100 years (Table 4.1, Figure 4.2) and all simulations reach the recovery target within 30 years.

Although the St. Mary's River (West Branch) salmon population has a maximum lifetime reproductive rate estimate of just over one (Section 2.5), this population is also expected to extirpate due to the effects of natural variability in survival (Figure 4.3). Extinction probabilities also increased rapidly, with 30% of the simulated populations extirpating within 30 years, and 86% of the simulated populations becoming extirpated within 60 years (Table 4.2, Figure 4.4). None of the 2000 simulated populations met the recovery target at any point within 100 years (Table 4.2, Figure 4.4) indicating a recovery probability of near zero based on the present dynamics. As was the case with the LaHave River (above Morgans Falls) population, abundance trajectories using the past (1980's) dynamics (Figure 4.3) indicate rapid population growth. None of the simulated population trajectories extirpate within 100 years (Table 4.2, Figure 4.4) and 97% of the simulated populations reach the recovery target within 30 years. Not all populations remain above the recovery target all of the time because of the low carrying capacity for age-1 parr estimated for this population (Table 2.2.1).

4.2 EFFECTS OF EXTREME ENVIRONMENTAL EVENTS

Extreme environmental events that markedly reduce the abundance of juvenile Atlantic salmon do occasionally occur. One such event potentially occurred in the fall of 2010 with very high water levels occurring shortly after the spawning season. Extremely high water events can lead to disturbance or destruction of redds or overwintering habitat for juveniles resulting in higher mortality. As reported in DFO (2012), based on electrofishing data from 11 sites in 2011, the mean fry density in 2011 was lower than the five-year mean fry density by 89% for the area above Morgans Falls and by 83% for the area below Morgans Falls (Figure 4.5). DFO (2012) concluded that "the degree to which these sharp declines in juvenile abundance are due to adult declines versus stochastic water conditions or some other factors is not known", based in part on the very low spawner abundance in 2010. The model results presented earlier afford the opportunity to investigate these values further. Projecting forward using the 2010 egg deposition, the electrofishing scalar and egg mortality rate (all as estimated in Section 2.2) would give an estimated fry density for 2011 of 2.23 (s.e.= 0.53) fry per 100 m^2. This value is nearly twice that observed (1.4 fry per 100 m^2) in the LaHave River (above Morgans Falls), indicating that low egg deposition was not the sole reason for this value, although it was a contributing factor. Further projections using the model results in Section 2.2 indicate that if the 2011 fry density is accurate and survivals equal the averages provided for the 2000's time period, the 2011 year class should contribute about 50 1SW salmon to the 2014 spawning run. This age combination (smoltification after two years and returning after one winter at sea) currently makes up the majority of the spawning run (e.g. 68% in 2010 – Bowlby et al. 2013a).

The effects of environmental variability and extreme events were investigated using the St. Mary's River (West Branch) population model. For each scenario described below, 2000 simulated population trajectories were run, each starting at the 2010 adult abundance. The St. Mary's example was chosen rather than the LaHave because it has an equilibrium population size greater than zero, and, therefore, would not become extinct in the absence of environmental variability, as shown by the deterministic model in Figure 4.6 (top left panel) (refer also to Section 2.5). However, when random variability is added to the projections (using the same life history parameter values as in the base model), the median time to extinction becomes just under 70 years with 10% of the populations becoming extinct within 40 years (Figure 4.6 – left column, second panel from the top). When extreme events are added, 10% of the populations are extinct in 22 years, and half of the populations are extinct within 40 years (Figure 4.6 – left column, third panel from the top). Changing the frequency and magnitude of the extreme events changes the extinction probabilities as expected (Figure 4.6 – left column, bottom two panels). However, when the same random variability and extreme event scenarios are modeled using the 1980's dynamics, none of the 10,000 simulated population trajectories become extinct and most met the recovery target. This highlights the resiliency that these salmon populations had in the past to environmental variability. Restoring this resiliency, resulting from distributing reproductive effort over multiple years coupled with higher survival, will be an important component of recovering Southern Upland Atlantic salmon.

5. POPULATION VIABILITY ANALYSIS OF RECOVERY SCENARIOS (TORS 21 AND 22)

To evaluate how the probability of extinction and probability of meeting the recovery target would be expected to vary with increased freshwater productivity and increased at-sea survival, 24 scenarios were evaluated for both the St. Mary's River (West Branch) and LaHave River (above Morgans Falls) salmon populations.

At-sea survival values considered in the analyses used the 1980's and 2000's dynamics as upper and lower estimates, respectively, with the two intermediate scenarios evenly spaced between these (i.e. at one-third and two-thirds the difference between past and present values) (Table 5.1).

Increased freshwater production was modeled by increasing smolt production by factors of 1.0 (no increase), 1.2 (20% increase), 1.5 (50% increase) and 2.0 (double or 100% increase). This is the same as changing the parr mortality parameter by equivalent amounts. For example, the annual mortality of parr older than age-1 was estimated to be 0.72 (Table 2.2.1) for the Lahave River (above Morgans Falls) population. This is a survival of 28% annually. The increased freshwater productivity scenario of 1.5 equates to a survival of 42% annually.

Each combination of increased freshwater productivity and at-sea survival was modeled for a total of 16 scenarios (see results below). In addition, eight other scenarios are presented to investigate the effects of extreme events. In these, freshwater productivity was increased by a factor of 1.5 and simulations were carried out for all four at-sea survival values. For each scenario, the probabilities of extinction and recovery were evaluated using 2000 simulated population trajectories.

Abundance trajectories, extinction probabilities and recovery probabilities for each scenario are provided in Figures 5.1, 5.2 and 5.3 for the LaHave River (above Morgans Falls) population, and in Figures 5.4, 5.5 and 5.6 for the St. Mary's River (West Branch) population. Associated numerical values are provided in Tables 5.2 and 5.3. The results of these analyses clearly indicate how close Southern Upland Atlantic salmon are to the threshold between becoming extinct and being viable. Panel "A" in each figure shows the results using the current dynamics; as previously described, both populations will extirpate in the absence of human intervention or a change in vital rates for some other reason. Panel "B" shows the effect of increasing freshwater productivity by 20%. This improvement is not large, but does markedly reduce extinction risk, even if marine mortality rates remain unchanged. For the LaHave River (above Morgans Falls) population, the probability of extinction within 30 years drops from 31% to 3% with this increase in survival. Similarly, for the St. Mary's River (West Branch) population, the probability of extinction drops from 31% to 4% with an increase in freshwater productivity of 20%. Increases of 50% (Panel C) drop the extinction probability to 0% for more than 50 years for both populations. Although small, numerically-viable populations are produced, none of the simulated population trajectories reached the recovery targets. Small increases in marine survival (Panels G to J) have a similar effect. None of the simulated populations extirpated in the one-thirds increase scenarios and a small proportion reached their recovery targets for both populations. The proportion reaching the recovery target increases as freshwater productivity increases (Figure 5.6; compare Panels G to J). Recovery probabilities exceed 50% in 50 years for all scenarios that include a two-thirds increase in at-sea survival (Panels M to X) and extinction probabilities are zero. Within limits, these conclusions are robust to how the frequency of extreme events is modeled (Panels E, K, Q, W, F, L, R, X). When the frequency of the extreme events is reduced, the probability of recovery increases and extinction probability is reduced (e.g. compare Panels H and K).

5.1 EFFECT OF TIME (STARTING POPULATION SIZE)

All the evidence indicates that in the absence of human intervention or a change in survival for some other reason, abundance of Southern Upland Atlantic salmon will continue to decline. To examine the effect of delaying recovery activities, the population viability analysis (base model) for the LaHave River (above Morgans Falls) population was re-run starting at 100%, 50%, 25% and 10% of the 2010 abundance estimates (300 small salmon and 53 large salmon). Using the present dynamics, further reductions in population size have the effect of shortening time to extinction (Figures 5.7 and 5.8). A reduction in starting population size of 50% reduces the time to which 50% of the simulated populations are extinct by about 10 years, whereas a reduction in size of 75% reduces the time to which 50% of the simulated populations are extinct to about 15 years. Similarly using the 1980's dynamics, time to recovery is similarly increased (Figures 5.7 and 5.8). The effects of further reductions in population size prior to the initiation of recovery are most evident in scenarios where populations are on the edge of recovery (Figure 5.9). For example, under Scenario B (an increase in freshwater production of 1.2 times), the probability of extinction within 25 years is 1% when the starting population size equals the 2010 abundance. This value increases to 10%, 45% and 97% for reductions in the starting population size of 50%, 25% and 10% of the 2010 abundance. The effect is not so great in Scenario G (an increase in at-sea survival of 1/3 – Table 5.1) because the increase in overall survival (i.e. survival from egg to adult) is greater than in Scenario B (Figure 5.9).

5.2 SENSITIVITY TO THE QUASI-EXTINCTION THRESHOLD

The results presented in this section are derived using a quasi-extinction threshold of 15 female salmon. Population viability analyses are known to be sensitive to the assumed threshold. This value is very low relative to the past abundances of salmon in these rivers. If depensatory dynamics exist, populations may not be able to recover from low abundances, even ones that are higher than this threshold. To evaluate the effects of the assumed quasi-extinction threshold on the estimated extinction probabilities, the analysis using the LaHave River (above Morgans Falls) model was re-run using sequentially increased quasi-extinction thresholds of 30, 50 and 100 female salmon (values that are still very low relative to past abundance). When scenarios are run using the 2000's dynamics, time to extinction decreases as the threshold is increased (Figure 5.10). However, this threshold has nearly no effect to time to recovery when the 1980's dynamics are used.

6. DISCUSSION, UNCERTANTIES AND CONCLUSIONS

Overall, the analyses presented in this document illustrate that the probability of extinction for Southern Upland Atlantic salmon is extremely high, but that only small changes in survival are required to markedly reduce this extinction risk. Larger increases in survival are required before populations will return to their past abundance.

The results presented here highlight some important differences between the dynamics of inner Bay of Fundy Atlantic salmon and Southern Upland Atlantic salmon. At-sea survival estimates for Southern Upland Atlantic salmon are roughly 10 times higher than those for inner Bay of Fundy salmon (Gibson et al. 2008b). For the inner Bay of Fundy populations, at-sea survival is low enough that it cannot be offset by recovery actions focused on other threats. Although at-sea survival of Southern Upland Atlantic salmon has decreased, it remains high enough that small increases in freshwater productivity are predicted to lead to small but viable populations, an outcome that is not possible within the inner Bay. However, increases in at-sea survival will be needed if populations in Southern Upland rivers are to be recovered to abundances above their respective conservation requirements. Readers are cautioned that, because of the fundamental differences in the dynamics of salmon populations in the two regions (both in fresh water and in the marine environment), extrapolating about the limiting effects of at-sea survival from the inner Bay of Fundy to the Southern Upland will lead to erroneous conclusions about its effects in the Southern Upland.

Although times to extinction and recovery are presented in this document, readers are cautioned not to interpret these values too literally, because prediction of extinction times using PVA is known to be highly uncertain (Taylor 1995; McCarthy et al. 1996; Ludwig 1999). As mentioned in the introduction to the PVA analyses, the most appropriate use of PVAs is to assess relative risk (e.g. Akçakaya and Raphael 1998; Beissinger and Westphal 1998; McCarthy et al. 2001) which can be used as a basis for choosing the most effective management strategy from a given set of possibilities (Lindenmayer and Possingham 1996). When comparing scenarios for Southern Upland Atlantic salmon, the important information is how much the time to extinction or recovery changes with when survival changes, not that extinction is predicted in (for example) 40 years.

The comparison of past (1980's) and present (2000's) viability from the PVA is of interest in that it highlights the loss of resiliency that the populations had in the past to environmental variability, most particularly to extreme environmental events. In all of the analyses here, no extinctions occurred as a result of environmental variability or extreme events when the simulations were carried out using the 1980's dynamics. Conversely, extinction risk increased rapidly when variability or the frequency of extreme events was increased using the 2000's dynamics. This resiliency arises from two sources. First, when a year class distributes its reproductive effort over a larger number of years (due to increased smolt age structure, increased variability in the number of years at sea prior to first spawning, and increased repeat spawning frequency), this increases the probability that some reproduction occurs in a good year. Second, lower maximum lifetime reproductive rates mean that the time it takes for the population to rebuild after an extreme event is much longer now than in the past. Therefore, the cumulative effect of extreme events has a greater influence on current viability.

Estimates of age- and stage-specific survivals and stage transition probabilities for both the LaHave River (above Morgans Falls) and the St. Mary's River (West Branch) are provided, however, it is more difficult to determine how these values compare with rates estimated for other populations (which would give some indication of what values would be achievable as a result of recovery actions). Despite there being a considerable amount of literature on salmon life history, there are relatively few estimates of survival that can be directly compared to the values presented here. For example, Cunjak and Therrien (1998) estimated survival from egg-to-smolt for Atlantic salmon in Catamaran Brook, NB, from 1990 to 1996 and obtained values between 0.16% and 0.52%. However, these values do not estimate maximum survival from egg-to-smolt because they do not take density dependent effects into consideration and thus are specific to the population abundance in a given year. The maximum survival estimates obtained for the LaHave and St. Mary's populations (1.7% and 3.4%, respectively) would be expected to be higher because they are estimates of the maximum survival that would occur at low population size and in the absence of density dependence (i.e. the slope at the origin). Using a model similar to that used here, Gibson et al. (2009b) estimated that the maximum survival from the egg-to-smolt was 0.46% for salmon in the Tobique River, NB, although this value was considered to be suggestive of either poor freshwater habitat quality or low population fitness relative to the environmental conditions in the Tobique River.

Similarly, the asymptotic smolt production values (i.e. carrying capacity of freshwater habitats for smolt) can also be difficult to compare, in part because smolt production per unit of habitat area varies with the mean age of the smolts (Symons 1979). Based on a review of values published in the literature, Symons (1979) concluded that age-2 smolt production should asymptote at 5 to 8 smolts per 100 m^2, and at 2 to 5 smolts per 100 m^2 for age-3 smolts. The asymptotic levels estimated here of 4.6 and 4.8 smolts per 100 m^2 for the LaHave and St. Mary's populations, respectively, are within this range. However, it is important to note that these are two of the larger remaining populations within the Southern Upland region and may not be representative of all populations within the region.

Throughout these analyses, the conservation requirement was used as the recovery target when assessing the probability of recovery, consistent with its definition when it was developed and its use as the critical-cautious boundary in the precautionary fisheries framework (see Bowlby et al. 2013a). In the analyses here, small increases in productivity and survival led to populations that were viable (conditional on model assumptions) at levels well below the conservation requirement. However, it is not known whether these populations would truly be viable in the longer term because the smaller populations may be at risk due to declining fitness caused by genetic effects, including inbreeding and loss of genetic variation (Frankham 2008). Lande and Barrowclough (1987) showed that an effective population size (N_e) of approximatly 500 individuals can maintain most genetic variability, although there are estimates of the number required that are lower. For Atlantic salmon, Elliott and Reilly (2003) found that an effective breeding population of 80 – 90 individuals was sufficient to maintain most of the genetic variability in populations introduced in Australia and Tasmania. Census population sizes (N_{census}) would be expected to be larger. Although overlapping generations, iteroparity and straying make the estimatation of N_e difficult, there are several studies that have estimated N_e and N_e /N_{census} ratios for salmonids (reviewed in Trzcinski et al. 2004). The average of the lower and upper limits of N_e /N_{census} ratios across taxa and studies give a range from 0.26 to 0.88. If we use the range of 0.26 – 0.88 and assume that a minimum of 80 – 100 individuals are necessary to maintain genetic variability, then the minimum total population size should be between 91 – 385. If Lande and Barrowclough"s (1987) more conservative estimate of a minimum effective population size of 500 individuals is used, then minimum census population size should be between 568 – 1,923 individuals. These values assume a closed population. If straying exists between rivers, the minimum census population size required to maintain genetic diversity would be lower. As discussed in Bowlby et al. (2013a), the recovery target should be revisited once populations are selected for recovery, recovery actions are identified, and information about the expected dynamics of the recovered population is obtained. In this document, the probability of recovery should be interpreted in the context of reaching the conservation requirement rather than in the context of preventing extinction. The sensitivity analyses with respect to the quasi-extinction threshold indicates how extinction risk increases if larger population sizes are required for longer term viability.

Acidification is a major threat to Southern Upland Atlantic salmon populations, one that has led to the extirpation of some populations in the region (see Section 4.1 in the Bowlby et al. 2013b). Although the increases in mortality rates expected to occur as a result of this threat are provided herein, it is difficult to determine from these analyses, whether increasing pH through liming would be sufficient to produce viable populations. Some mortality resulting from pH would be expected for both study populations, although for the St. Mary's this would be due to acid deposition events associated with rainfall rather than low mean annual pH. Therefore, liming would be expected to increase the productivity of the St. Mary's and LaHave populations, and to influence freshwater habitat quality in more highly acidified rivers to a greater extent. Additionally, if liming increased the overall condition of smolts, their at-sea survival might be expected to be higher.

Overall, the retrospective examination of the recreational fishery on the LaHave River (above Morgans Falls) and St. Mary's (West Branch) populations indicate that the fisheries did reduce population size, but that this reduction was not great enough in and of itself to be a major driver of the overall population decline, particularly after the switch to hook-and-release regulations. The effect of the fishery in the 2000's was negligible (assuming a 4% hook-and-release mortality rate) given the magnitude of the reported catches on the LaHave River and the escapement counts at the Morgans Falls fishway . However, at an assumed hook-and-release mortality rate of 20%, overall productivity was reduced by approximately 8%. Hook-and-release mortality rates higher than 4% are possible given that the fishery in recent years has been open when water temperatures are warmer (i.e. above 12°C). These results are conditional on the accuracy of the reported catch (under-reporting would lead to an under-estimate of impact). Additionally, the effect of any future recreational fishery would depend on the intensity and the timing of fishing activities.

Life history parameter estimates, dynamics and population viability were assessed using data for two Southern Upland Atlantic salmon populations: the LaHave River (above Morgans Falls) and the St. Mary's River (West Branch). Estimates of age- and stage-specific survival differed between the two populations, most notably for parr and for immature salmon while at sea. It is possible that some of the differences in parameter estimates could arise due to the way the data are collected. For example, if smolt abundance in the LaHave is underestimated (e.g. due to changing efficiencies of the smolt monitoring facility associated with power generation), or it is overestimated in the St. Mary's (i.e. due to low recapture rates), the return rate estimates would be more similar than those estimated here. However, such errors in estimation would have little effect on the conclusions about population viability. Because the model covers the entire life cycle, if smolt abundance is underestimated, for example, survival to the smolt stage is overestimated, but the smolt to adult return rates are then overestimated by an equivalent amount. The lifetime reproductive rates, which are the values that ultimately determine viability, would remain the same.

While the conclusions about viability are relatively robust to under- or over-estimation of individual survival estimates, predictions about the effectiveness of individual recovery actions would be more sensitive to this source of uncertainty. For example, the mortality rate estimates for age-1 and older parr were 72% and 34% for the LaHave (above Morgans Falls) and St. Mary's (West Branch) populations, respectively. The reason the LaHave estimate is higher is not known, but could be related to the impact of threats like the presence of smallmouth bass in the LaHave watershed or water quality (differences in pH) between the rivers. If mortality was overestimated for this life stage in the LaHave, it would imply that addressing these types of threats during recovery (e.g. reducing smallmouth bass predation) would be more effective than they actually would be.

When interpreting the at-sea survival estimates provided in this document, it is important to consider exactly what they represent. For the LaHave River (above Morgans Falls) population, smolt are enumerated as they migrate downstream at Morgans Falls, 25 km above the tidal limit (Hubley et al. 2008). Similarly, adults are enumerated as they ascend the fish ladder bypassing these falls. Although the effect of the recreational fishery on the return rate estimates has been accounted for, other sources of mortality (e.g. predation on smolts, poaching) have not been. Any recovery actions that increase survival of salmon migrating in fresh water would thus have the same effect on population viability as an equivalent increase in survival while they are at sea. Figure 2.3.1 highlights that the majority of smolt mortality observed from acoustically tagged fish in Southern Upland rivers took place in fresh water or the inner estuary (Halfyard et al. 2012).

The population viability analyses illustrate the expected population trajectories for a specific set of life history parameter values, but do not include linkages among the various survival rates. For example, it has been suggested that survival of fish in large schools is enhanced when traveling through predator fields compared to fish traveling singly or in small schools (Cairns 2001). As another example, the age-of-smoltification may be linked to the growth rates of parr, which can be density dependent.

Both the trends in abundance provided in Bowlby et al. (2013a) and the information on population dynamics presented here indicate that abundance of Southern Upland Atlantic salmon is expected to continue to decline in the absence of human intervention or a change in life history parameters for some other reason. As shown in Section 5, both the probability of extinction and the time to recovery increase if abundance decreases further before recovery actions are initiated. In addition, it is expected that there are risks to the population of being at low population size, such as the loss of genetic variation and inbreeding depression. The scenarios do not fully explore the uncertainties in how small a population may get before it cannot be recovered (e.g. the models do not include depensatory processes). However, the sensitivity analysis with respect to the quasi-extinction threshold shows that the risk of extinction increases as this threshold is increased. Irrespective of the absolute value of this threshold, further reductions in abundance do take Southern Upland Atlantic salmon populations closer to this limit.

The exploration on the effect of starting population size on population viability highlights the risks associated with delaying recovery actions (if they are to be initiated) for Southern Upland Atlantic salmon. As above, it does not fully account for these risks because the assumption that fitness does not change at low population size is inherent in the model (i.e. modeled populations still have the capacity to grow in size regardless of how small they get). As discussed above, there are risks associated with being at low population size that are expected to lead to lower fitness and thus a reduced capacity for population increase. Recovery is therefore expected to become more difficult if abundance continues to decline, as is expected for these populations with the continued passage of time.

7. ACKNOWLEDGMENTS

The authors thank Sean Mitchell and Gerald Chaput for helpful comments on an earlier draft of this manuscript.

8. REFERENCES

Akcakaya, H.R., and M.G. Raphael. 1998. Assessing human impact despite uncertainty: Viability of the Northern Spotted Owl metapopulation in northwestern USA. Biodiversity and Conservation 7: 875-894.

Amiro, P.G. 1993. Habitat measurement and population estimation of juvenile Atlantic salmon (*Salmo salar*). In Production of juvenile Atlantic salmon, *Salmo salar*, in natural waters. Edited by R. J. Gibson and R. E. Cutting. Canadian Special Publications of Fisheries and Aquatic Sciences 118. pp. 81-97.

Amiro, P.G., and E.M. Jefferson. 1997. Status of Atlantic salmon in Salmon Fishing Area 21, in 1996, with emphasis on the upper LaHave River, Lunenburg Co., Nova Scotia. Fisheries and Oceans Canada. Canadian Science Advisory Secretariat Research Document. 97/25.

Amiro, P.G., and E.M. Jefferson. 1998. Status of Atlantic salmon in Salmon Fishing Area 21, in 1997, with emphasis on the upper LaHave River, Lunenburg Co., Nova Scotia. Fisheries and Oceans Canadian Science Advisory Secretariat Research Document 1998/039.

Amiro, P.G., E.M. Jefferson, and C.J. Harvie. 1996. Status of Atlantic salmon in Salmon Fishing Area 21, in 1995, with emphasis on the upper LaHave River, Lunenburg. Co., Nova Scotia. Department of Fisheries and Oceans. Atlantic Fisheries Research Document 96/126.

Amiro, P.G., A.J. McNeill, and D.A. Longard. 1989. Results of surveys and electrofishing in the Stewiacke River, 1984 to 1988 and the St. Mary's River, 1985 and 1986. Canadian Data Report of Fisheries and Aquatic Sciences 764.

Barnthouse, L.W., R.J. Klauda, D.S. Vaughan, and R.L. Kendall. 1988. Science, law, and the Hudson River power plants: A case study in environmental assessment. American Fisheries Society Monograph 4. American Fisheries Society, Bethesda, Maryland.

Beissinger, S.R., and S.R. McCullough. 2002. Population viability analysis. The University of Chicago Press, Chicago, Illinois.

Beissinger, S.R., and M.I. Westphal. 1998. On the use of demographic models of population viability in endangered species management. Journal of Wildlife Management 62: 821-841.

Bowlby, H.D., and A.J.F. Gibson. 2011. Reduction in fitness limits the useful duration of supplementary rearing in an endangered salmon population. Ecological Applications 21: 3032-3048.

Bowlby, H.D., A.J.F. Gibson, and A. Levy. 2013a. Recovery Potential Assessment for Southern Upland Atlantic salmon: Status, past and present abundance, life history and trends. Fisheries and Oceans Canada. Canadian Science Advisory Secretariat Research Document 2013/005.

Bowlby, H.D., S.C. Mitchell, T.L. Horsman, and A.J.F. Gibson. 2013b. Recovery Potential Assessment for Southern Upland Atlantic salmon: Habitat requirements and status, threats to populations, and potential mitigation options. Fisheries and Oceans Canada. Canadian Science Advisory Secretariat Research Document 2013/006.

Cairns, D.K. (Editor). 2001. An evaluation of the possible causes of decline in pre-fishery North American Atlantic salmon. Canadian Technical Report of Fisheries and Aquatic Sciences 2358.

Carlin, B.P., and T.A. Louis. 1996. Bayes and empirical Bayes methods for data analysis. Volume 69 of *Monographs on Statistics and Applied Probability.* Chapman and Hall, London, United Kingdom.

Chib, S., and E. Greenberg. 1995. Understanding the Metropolis-Hastings algorithm. The American Statistician 49: 327-335.

Chilcote, M.W., K.W. Goodson, and M.R. Falcy. 2011. Reduced recruitment performance in natural populations of anadromous salmonids associated with hatchery-reared fish. Canadian Journal of Fisheries and Aquatic Sciences 68: 511-522.

COSEWIC. 2010. COSEWIC assessment and status report on the Atlantic salmon *Salmo salar* (Nunavik population, Labrador population, Northeast Newfoundland population, South Newfoundland population, Southwest Newfoundland population, Northwest Newfoundland population, Quebec Eastern North Shore population, Quebec Western North Shore population, Anticosti Island population, Inner St. Lawrence population, Lake Ontario population, Gaspe-Southern Gulf of St. Lawrence population, Eastern Cape Breton population, Nova Scotia Southern Upland population, Inner Bay of Fundy population Outer Bay of Fundy population) in Canada. Committee on the Status of Endangered Wildlife in Canada. Ottawa, Ontario. 136 p. Available at [Internet] http://www.sararegistry.gc.ca/virtual_sara/files/cosewic/sr_Atlantic%20Salmon_2011_e.pdf (accessed 1 March 2012).

Cunjak, R.A. and J. Therrien. 1998. Inter-stage survival of wild juvenile Atlantic salmon, *Salmo salar* L. Fisheries Management and Ecology 5: 209–223.

Cutting, R.E., E.M. Jefferson and S.F. O'Neil. 1987. Status of the Atlantic salmon of the LaHave River, Nova Scotia, in 1986 and forecast of returns in 1987. Fisheries and Oceans Canada. Canadian Science Advisory Secretariat Research Document 1987/106.

Dennis, B., P. Munholland, and J.M. Scott. 1991. Estimation of growth and extinction parameters for endangered species. Ecological Monographs 61: 115–143.

Deriso, R.B., T.J. Quinn, II, and P.R. Neal. 1985. Catch-age analysis with auxiliary information. Canadian Journal of Fisheries and Aquatic Sciences 42: 815-824.

DFO. 2011. Status of Atlantic salmon in Salmon Fishing Areas (SFAs) 19-21 and 23. Fisheries and Oceans Canada. Canadian Science Advisory Secretariat Science Response 2011/005.

DFO. 2012. Status of Atlantic salmon in Salmon Fishing Areas (SFAs) 19-21 and 23. Fisheries and Oceans Canada. Canadian Science Advisory Secretariat Science Response 2012/014.

Efron, B., and R.J. Tibshirani. 1993. An Introduction to the Bootstrap. International Thomson Publishing. New York, New York.

Elliott, N.G., and A. Reilly. 2003. Likelihood of bottleneck event in the history of the Australian population of Atlantic salmon (*Salmo salar* L.). Aquaculture 215: 31-44.

Farmer, G.J. 2000. Effects of low environmental pH on Atlantic salmon (*Salmo salar* L.) in Nova Scotia. Fisheries and Oceans Canada. Canadian Stock Assessment Secretariat Research Document 2000/050.

Farmer, G.J., T.R. Goff, D. Ashfield, and H.S. Samant. 1980. Some effects of the acidification of Atlantic salmon rivers in Nova Scotia. Canadian Technical Report of Fisheries and Aquatic Sciences 972.

Fournier, D. 1996. An introduction to AD Model Builder for use in nonlinear modelling and statistics. Otter Research Ltd., Nanaimo, British Columbia.

Fournier, D.A., and C.P. Archibald. 1982. A general theory for analyzing catch at age data. Canadian Journal of Fisheries and Aquatic Sciences 39: 1195-1207.

Frankham, R. 2008. Genetic adaptation to captivity in species conservation programs. Molecular Ecology 17: 325–333.

Gamerman, D. 2000. Markov Chain Monte Carlo: Stochastic Simulation for Bayesian Inference. CRC Press, London, United Kingdom.

Gibson, A.J.F. 2006. Population Regulation in Eastern Canadian Atlantic salmon (*Salmo salar*) populations. Fisheries and Oceans Canada. Canadian Science Advisory Secretariat Research Document 2006/016.

Gibson, A.J.F., and P.G. Amiro. 2003. Abundance of Atlantic salmon (*Salmo salar*) in the Stewiacke River, NS, from 1965 to 2002. Fisheries and Oceans Canada. Canadian Science Advisory Secretariat Research Document 2003/108.

Gibson, A.J.F., and P.G. Amiro. 2007. Predicting the Effects of Recovery Activities on Atlantic Salmon Populations. In Proceedings of the Acid Rain Mitigation Workshop, Bedford Institute of Oceanography, May 26th and 27th, 2006. Edited by M. Brylinsky and L. Hinks. pp. 15-23.

Gibson A.J.F., H.D. Bowlby, and P.G. Amiro. 2008a. Are wild populations ideally distributed? Variations in density-dependent habitat use by age class in juvenile Atlantic salmon (*Salmo salar*). Canadian Journal of Fisheries and Aquatic Sciences 65: 1667-1680.

Gibson, A.J.F., H.D. Bowlby, J.R. Bryan, and P.G. Amiro. 2008b. Population viability analysis of inner Bay of Fundy Atlantic salmon with and without Live Gene Banking. Fisheries and Oceans Canada. Canadian Science Advisory Secretariat Research Document 2008/057.

Gibson, A.J.F., R.A. Jones, and P.G. Amiro. 2008c. Equilibrium analyses of the recovery feasibility of four Atlantic salmon (*Salmo salar*) populations in Nova Scotia and Southwest New Brunswick. Department of Fisheries and Oceans Canadian Science Advisory Secretariat Research Document 2008/010.

Gibson, A.J.F., H.D. Bowlby, D.L. Sam, and P.G. Amiro. 2009a. Review of DFO Science information for Atlantic salmon (*Salmo salar*) populations in the Southern Upland region of Nova Scotia. Fisheries and Oceans Canada. Canadian Science Advisory Secretariat Research Document 2009/081.

Gibson, A.J.F., R.A. Jones, and H.D. Bowlby. 2009b. Equilibrium analyses of a population's response to recovery activities: a case study with Atlantic salmon. North American Journal of Fisheries Management 29: 958-974.

Gibson, A.J.F., H.D. Bowlby, D. Hardie, and P. O'Reilly. 2011. Populations on the brink: Atlantic salmon (*Salmo salar*) in the Southern Upland Region of Nova Scotia, Canada. North American Journal of Fisheries Management 31: 733–741.

Halfyard, E.A., D.E. Ruzzante, M.J.W. Stokesbury, A.J.F. Gibson, and F.G. Whoriskey. 2012. Estuarine migratory behaviour and survival of Atlantic salmon smolts from the Southern Upland, Nova Scotia, Canada. Journal of Fish Biology 81: 1626–1645.

Hayes, D.B., C.P. Ferreri, and W.W. Taylor. 1996. Linking fish habitat to their population dynamics. Canadian Journal of Fisheries and Aquatic Sciences 53 (Supplement 1): 383-390.

Hilborn, R. 2001. Risk analysis for salmon spawning reference levels. In Stock, Recruitment and Reference Points, Assessment and Management of Atlantic salmon. Edited by E. Prevost and G. Chaput. Institute for Agricultural Research, Paris, France. pp. 177-193.

Hilborn, R., and M. Mangel. 1997. The ecological detective: Confronting models with data. Princeton University Press, New Jersey.

Hilborn, R. and C.J. Walters. 1992. Quantitative fisheries stock assessment: Choice, dynamics and uncertainty. Chapman and Hall, New York, New York.

Holt, C.A., and R.M. Peterman. 2008. Uncertainties in population dynamics and outcomes of regulations in sockeye salmon (*Oncorhynchus nerka*) fisheries: Implications for management. Canadian Journal of Fisheries and Aquatic Sciences 65: 1459-1474.

Hubley, P.B. 2010. Examining mortality of mature Atlantic salmon (*Salmo salar*) and its effects on iteroparity. Masters of Science thesis, Acadia University, Wolfville, Nova Scotia.

Hubley, P.B., and A.J.F. Gibson. 2011. A model for estimating mortality of Atlantic salmon, *Salmo salar*, between spawning events. Canadian Journal of Fisheries and Aquatic Sciences 68: 1635-1650.

Hubley, P.B., P.G. Amiro, A.J.F. Gibson, G.L. Lacroix, and A.M. Reddin. 2008. Survival and behaviour of migrating Atlantic salmon (*Salmo salar* L.) kelts in river, estuarine and coastal habitat. International Council for the Exploration of the Sea. Journal of Marine Science 65: 1626-1634.

ICES. 2009. Report of the Working Group on North Atlantic Salmon (WGNAS), 30 March–8 April, Copenhagen, Denmark. . International Council for the Exploration of the Sea Council Meeting 2009/ACOM:06. 282 pp.

Johnston, C.E., R.L. Saunders, E.B. Henderson, P.R. Harmon, and K. Davidson. 1984. Chronic effects of low pH on some physiological aspects of smoltification in Atlantic salmon (*Salmo salar*). Canadian Technical Report of Fisheries and Aquatic Sciences 1294.

Jonsson, B., and N. Jonsson. 2006. Cultured Atlantic salmon in nature: a review of their ecology and interaction with wild fish. International Council for the Exploration of the Sea. Journal of Marine Science 63: 1162-1181.

Korman, J., D.R. Marmorek, G.L Lacroix, P.G. Amiro, J.A. Ritter, W.D. Watt R.E. Cutting, and D.C.E. Robinson. 1994. Development and evaluation of a biological model to assess regional-scale effects of acidification on Atlantic salmon (*Salmo salar*). Canadian Journal of Fisheries and Aquatic Sciences 51: 662-680.

Lacroix, G.L. 1985. Survival of eggs and alevins of Atlantic salmon (*Salmo salar*) in relation to the chemistry of interstitial water in redds in some acidic streams of Atlantic Canada. Canadian Journal of Fisheries and Aquatic Sciences 42: 92-299.

Lacroix, G.L., D.J. Gordon, and D.J. Johnston. 1985. Effects of low environmental pH on the survival, growth, and ionic composition of postemergent Atlantic salmon (*Salmo salar*). Canadian Journal of Fisheries and Aquatic Sciences 42: 768-775.

Lande, R., and G.F. Barrowclough. 1987. Effective population size, genetic variation, and their use in population management. In Viable populations for conservation. Edited by M.E. Soule. Cambridge University Press, New York, New York. pp. 87–123.

Lande, R., S. Engen, and B.-E. Saether. 2003. Stochastic population dynamics in ecology and conservation. Oxford University Press, New York, New york.

Legault, C.M. 2005. Population Viability Analysis of Atlantic salmon in Maine, USA. Transactions of the American Fisheries Society 134: 539-562.

Lindenmayer, D.B., and H.P. Possingham. 1996. Ranking conservation and timber management options for Leadbeater's possum in southeastern Australia using Population Viability Analysis. Conservation Biology 10: 235-251.

Ludwig, D. 1999. Is it meaningful to estimate a probability of extinction? Ecology 80: 293-310.

McAllister, M.K., and G.P. Kirkwood. 1998. Bayesian stock assessment: a review and example application using the logistic model. ICES Journal of Marine Sciences 55: 1031-1060.

McAllister, M.K., E.K. Pikitch, A.E. Punt, and R. Hilborn. 1994. A Bayesian approach to stock assessment and harvest decisions using the sampling/importance resampling algorithm. Canadian Journal of Fisheries and Aquatic Sciences 51: 2673-2687.

McCarthy, M.C., M.A. Burgman, and S. Ferson. 1996. Logistic sensitivity and bounds on extinction risks. Ecological Modelling 86: 297-303.

McCarthy M.A., H.P. Possingham, J.R. Day, and A.J. Tyre. 2001. Testing the accuracy of population viability analysis. Conservation Biology 15: 1030–1038.

McCarthy, M.A., S.J. Andelman, and H.P. Possingham. 2003. Reliability of Relative Predictions in Population Viability Analysis. Conservation Biology 17: 982–989.

McGinnity, P., P. Prodohl, N. O'Maoileidigh, R. Hynes, D. Cotter, N. Baker, B. O'Hea, and A. Ferguson. 2004. Differential lifetime success and performance of native and non-native Atlantic salmon examined under communal natural conditions. Journal of Fish Biology 65(Supplement A): 173-187.

Merritt, M.F., and T.J. Quinn, II. 2000. Using perceptions of data accuracy and empirical weighting information: assessment of a recreational fish population. Canadian Journal of Fisheries and Aquatic Sciences 57: 1459-1469.

Moussalli, E., and R. Hilborn. 1986. Optimal stock size and harvest rate in multistage life history models. Canadian Journal of Fisheries and Aquatic Sciences 43: 135-141.

Myers, R.A., A.A. Rosenberg, P.M. Mace, N.J. Barrowman, and V.R. Restrepo. 1994. In search of thresholds for recruitment overfishing. International Council for the Exploration of the Sea. Journal of Marine Science 51: 191-205.

Myers, R.A., J. Bridson, and N.J. Barrowman. 1995. Summary of worldwide stock and recruitment data. Canadian Technical Report of Fisheries and Aquatic Sciences 2024.

O'Grady, J.J., D.H. Reed, B.W. Brook, and R. Frankham. 2004. What are the best correlates of predicted extinction risk? Biological Conservation 118: 513-520.

O'Neil, S.F., and C.J. Harvie. 1995. Estimates of Atlantic salmon stock status on the eastern shore of Nova Scotia, Salmon Fishing Area 20, in 1994. Fisheries and Oceans Canada. Atlantic Fisheries Research Document 95/132.

O'Neil, S.F., and D.A.B. Swetnam. 1984. Collation of Atlantic salmon sport catch statistics, Maritime Provinces, 1970-79. Canadian Data Report of Fisheries Aquatic Sciences 481.

O'Neil, S.F., C.J. Harvie, and D.A. Longard. 1997a. Stock Status of Atlantic Salmon *(Salmo salar L.)* on the Eastern Shore of Nova Scotia, Salmon Fishing Area 20, in 1996. Fisheries and Oceans Canada. Canadian Stock Assessment Secretariat Research Document 97/024.

O'Neil, S.F., C.J. Harvie, and D.A. Longard. 1997b. Stock Status of Atlantic Salmon on the Eastern Shore of Nova Scotia, Salmon Fishing Area 20, in 1995. Fisheries and Oceans Canada. Canadian Stock Assessment Secretariat Research Document 97/118.

O'Neil, S.F., C.J. Harvie, D.A. Longard, and P.G. Amiro. 1998. Stock status of Atlantic salmon (*Salmo salar* L.) on the Eastern Shore of Nova Scotia, Salmon Fishing Area 20 in 1997. Fisheries and Oceans Canada. Canadian Stock Assessment Secretariat Research Document 98/37.

O'Reilly, P., S. Rafferty, and J. Gibson. 2012. Within- and among-population genetic variation in the Southern Upland Designatable Unit of Maritime Atlantic Salmon (*Salmo salar* L.). Fisheries and Oceans Canada. Canadian Science Advisory Secretariat Research Document 2012/077.

Punt, A.E., and R. Hilborn. 1997. Fisheries stock assessment and the Bayesian approach. Reviews in Fish Biology and Fisheries 7: 35-63.

Quinn, T.J., and R.B. Deriso. 1999. Quantitative Fish Dynamics. Oxford University Press. New York, New York.

Reed, J.M., L.S. Mills, J.B. Dunning, E.S. Menges, K.S. McKelvey, R. Frye, S.R. Beissinger, M.-C. Anstett, and P. Miller. 2002. Emerging issues in Population Viability Analysis. Conservation Biology 16: 7-19.

Shelton, P.A., B. Best, A. Cass, C. Cyr, D. Duplisea, J. Gibson, M. Hammill, S. Khwaja, M. Koops, K. Martin, B. O'Boyle, J. Rice, A. Sinclair, K. Smedbol, D. Swain, L. Velez-Espino, and C. Wood. 2007. Assessing recovery potential: long-term projections and their implications for socio-economic analysis. Fisheries and Oceans Canada. Canadian Science Advisory Secretariat Research Document 2007/045.

Strothotte, E., G.J. Chaput, and H. Rosenthalt. 2005. Seasonal growth of wild Atlantic salmon (*Salmo salar* L.) juveniles and implications on age at smoltification. Journal of Fish Biology 67: 1585-1602.

Swetnam, D. A.B., and S.F. O'Neil. 1984. Collation of Atlantic salmon sport catch statistics, Maritime Provinces, 1980-83. Canadian Data Report of Fisheries Aquatic Sciences 450.

Symons, P.E.K. 1979. Estimated escapement of Atlantic salmon (*Salmo salar*) for maximum smolt production in rivers of different productivity. Journal of the Fisheries Research Board of Canada 36: 132–140.

Taylor, B.L. 1995. The reliability of using Population Viability Analysis for Risk Classification of species. Conservation Biology 9(3), 551–558.

Trzcinski, M.K., A.J.F. Gibson, P.G. Amiro, and R.G. Randall. 2004. Inner Bay of Fundy Atlantic salmon critical habitat case study. Fisheries and Oceans Canada. Canadian Science Advisory Secretariat Research Document 2004/114.

Walters, C., and D. Ludwig. 1993. Calculation of Bayes posterior distributions for key population parameters. Canadian Journal of Fisheries and Aquatic Sciences 51: 713-722.

Watt, W.D. 1987. A summary of the impact of acid rain on Atlantic salmon *(Salmo salar*) in Canada. Water, Air, and Soil Pollution 35: 27-35.

Weir, L.K., J.A. Hutchings, I.A. Fleming, and S. Einum. 2004. Dominance relationships and behavioural correlates of individual spawning success in farmed and wild male Atlantic salmon, *Salmo salar*. Journal of Animal Ecology 73: 1069-1079.

9. TABLES

Table 2.2.1. Maximum likelihood estimates (MLE) for the life history parameters characterizing freshwater productivity for the Atlantic salmon populations in the LaHave River (above Morgans Falls) and in the West Branch of the St. Mary's River. Also shown are the estimates of the maximum survival from egg to smolt and the asymptotic recruitment level derived for smolts. The probability of smoltification in two time periods was estimated for the LaHave but not for the St. Mary's River population. The conservation requirements are provided as indicators of the potential relative size of the populations.

	LaHave River (above Morgans Falls)		St. Mary's River (West Branch)	
	MLE	Std. Deviation	MLE	Std. Deviation
Conservation Requirement :	6.25 million eggs		5.26 million eggs	
Age and Stage specific parameter values:				
M_{Egg}	0.88	0.04	0.92	0.01
α	0.58	0.07	0.67	0.10
R_{asy}	35.53	12.53	11.76	2.52
M_{Parr}	0.72	0.07	0.34	0.10
j_2 (before 1985)	0.83	0.04	0.85	0.02
j_3 (before 1985)	1.00	0.00	1.0 (assumed)	
j_2 (after 1985)	0.60	0.06	as above	
j_3 (after 1985)	0.99	0.01	as above	
Egg to smolt dynamics:				
$\breve{\alpha}$ (before 1985)	0.017	0.002	0.034	0.006
$\breve{R}_{asy}$ (before 1985)	147,700	55,506	104,120	29,861
$\breve{\alpha}$ (after 1985)	0.013	0.002	as above	
$\breve{R}_{asy}$ (after 1985)	119,690	44,762	as above	

Table 2.2.2. A summary of the average return rates (percent) of 1SW and 2SW wild Atlantic salmon for the 1980 to 1989 and 2000 to 2009 time periods for the populations in the Lahave River (above Morgans Falls) and in the West Branch of the St. Mary's River. The values are the maximum likelihood estimates from the life history models. Two sets of values are provided: return rates to the river mouth, and return rates to enumeration (either at the Morgans Falls fish ladder on the LaHave River or in the fall assessment on the West Branch of the St. Mary's River). The difference between the two sets of values is an indicator of the effect of the recreational fishery on the proportion of the population surviving to spawn in each time period.

	LaHave River (above Morgans Falls)		St. Mary's River (West Branch)	
	1980-1989	2000-2009	1980-1989	2000-2009
Return rates to river mouth (%)				
1SW mean	7.28	2.25	3.33	1.18
1SW minimum	2.87	1.19	1.17	0.54
1SW maximum	17.60	4.14	5.52	2.11
2SW mean	0.74	0.33	0.74	0.09
2SW minimum	0.31	0.10	0.18	0.00
2SW maximum	1.21	0.52	1.54	0.30
Return rates including recreational fishery removals (%)				
1SW mean	5.30	2.24	2.46	1.17
1SW minimum	2.35	1.18	0.86	0.54
1SW maximum	12.31	4.13	4.19	2.08
2SW mean	0.70	0.33	0.70	0.09
2SW minimum	0.31	0.10	0.13	0.00
2SW maximum	1.19	0.52	1.52	0.30

Table 2.3.1. Cumulative survival (%) and standardized survival (% per km of habitat zone length) of smolts upon exit from four habitat-zones (FW – fresh water; IE – inner estuary; OE – outer estuary; Bay / Overall). Smolts detected dead less than 1 km from release were excluded from estimates of observed survival. From Halfyard et al. (2012).

	Observed Cumulative Survival Upon Exit			
River-Year	FW	IE	OE	BAY /Overall
LaHave	76.5% 98.9% $\cdot km^{-1}$	76.5% 100.0% $\cdot km^{-1}$	73.5% 99.7% $\cdot km^{-1}$	73.5% 100.00% $\cdot km^{-1}$
Gold	100.0% 100.0% $\cdot km^{-1}$	88.2% 92.4% $\cdot km^{-1}$	79.4% 97.8% $\cdot km^{-1}$	61.8% 97.6% $\cdot km^{-1}$
St. Mary's	79.4% 99.3% $\cdot km^{-1}$	76.5% 98.7% $\cdot km^{-1}$	73.5% 98.7% $\cdot km^{-1}$	67.6% 98.3% $\cdot km^{-1}$
West 2008	78.9% 97.0% $\cdot km^{-1}$	52.6% 83.8% $\cdot km^{-1}$	47.4% 96.5% $\cdot km^{-1}$	47.4% 100.0% $\cdot km^{-1}$
West 2009	96.0% 99.5% $\cdot km^{-1}$	76.0% 90.5% $\cdot km^{-1}$	72.0% 98.3% $\cdot km^{-1}$	68.0% 98.8% $\cdot km^{-1}$
West 2010	71.9% 95.5% $\cdot km^{-1}$	54.5% 91.0% $\cdot km^{-1}$	51.5% 98.0% $\cdot km^{-1}$	39.4% 95.0% $\cdot km^{-1}$

Table 2.4.1. Mean annual mortality rate (M) and probability of consecutive spawning (p) of repeat spawning Atlantic salmon from the LaHave River, Nova Scotia, Canada, during three time periods. Notation is: M1 – annual mortality in the first year, M2 – annual mortality in the second year, MG – male grilse, MS – male 2SW salmon. F – female, p – probability of consecutive spawning, FG – female grilse, and FS – female salmon. From Hubley and Gibson (2011).

		Period	
Parameter	1979-1988	1989-1998	1999-2008
$M1_{MG}$	0.88	0.92	0.95
$M1_{MS}$	0.51	0.59	0.64
$M1_{F}$	0.75	0.81	0.86
M2	0.60	0.73	0.74
p_{MG}	0.058	0.055	0.062
p_{MS}	0.022	0.026	0.022
p_{FG}	0.028	0.033	0.020
p_{FS}	0.033	0.071	0.043

Table 2.5.1. A summary of the number of eggs produced per smolt throughout its life (EPS) for wild Atlantic salmon for the 1980 to 1989 and 2000 to 2009 time periods for the populations in the LaHave River (above Morgans Falls) and in the West Branch of the St. Mary's River. The values are the maximum likelihood estimates from the life history models. Two sets of values are provided: EPS derived using return rates to the river mouth, and using return rates to the time of the assessments during the fall. The difference in the values is an indicator of the effect of the recreational fishery on the lifetime egg production per smolt in each time period.

	LaHave River (above Morgans Falls)		St. Mary's River (West Branch)	
	1980-1989	2000-2009	1980-1989	2000-2009
EPS using return rates to river mouth				
Mean	217.55	63.03	132.07	30.46
Minimum	86.95	28.96	41.11	11.64
Maximum	489.06	111.30	239.77	62.70
EPS including recreational fishery removals				
Mean	168.42	62.68	107.86	30.04
Minimum	74.66	28.73	29.80	11.60
Maximum	364.10	111.14	204.93	62.13

Table 2.5.2. A summary of the equilibrium population sizes and maximum lifetime reproductive rates for wild Atlantic salmon for the 1980 to 1989 and 2000 to 2009 time periods for the populations in the LaHave River (above Morgans Falls) and in the West Branch of the St. Mary's River. The values are the maximum likelihood estimates from the life history models. Two sets of values are provided: those derived using return rates to the river mouth, and those derived based on survival to the time of the assessments during the fall. The difference in the values is an indicator of the effect of the recreational fishery on the population dynamics in each time period.

	LaHave River (above Morgans Falls)		St. Mary's River (West Branch)	
	1980-1989	2000-2009	1980-1989	2000-2009
Values using return rates to river mouth				
Equilibrium egg deposition				
mean	23,188,000	0	10,651,000	71,262
minimum	3,898,900	0	1,179,800	0
maximum	63,289,000	4,378,700	21,864,000	3,428,700
Equilibrium smolt abundance				
mean	106,590	0	80,646	2,339
minimum	44,841	0	28,703	0
maximum	129,410	39,342	91,189	54,680
Max. lifetime reproductive rate				
mean	3.59	0.84	4.44	1.02
minimum	1.44	0.39	1.38	0.39
maximum	8.08	1.49	8.05	2.11
Values including recreational fishery removals				
Equilibrium egg deposition				
mean	15,931,000	0	8,130,100	27,932
minimum	2,083,800	0	2,311	0
maximum	44,832,000	4,359,900	18,237,000	3,369,300
Equilibrium smolt abundance				
mean	94,593	0	75,377	929
minimum	27,910	0	77	0
maximum	123,130	39,228	88,991	54,226
Max. lifetime reproductive rate				
mean	2.78	0.84	3.62	1.01
minimum	1.23	0.38	1.00	0.39
maximum	6.01	1.49	6.88	2.09

Table 3.2.1. Mortality rates (%) and toxic accumulation (TD - proportion dying weekly) and of juvenile Atlantic salmon as a function of surface pH as derived from the toxicity functions in Korman et al. (1994). Values outside the interval 0% - 100% were assigned the limit value. Rates and pH values are specific to the time period. Mortality rates are in addition to natural mortality and mortality from other causes.

Life Stage	Time Period	Rate	Average Surface pH 4.50	4.75	5.0	5.25	5.50
Egg	Nov. – Apr.	Mortality	57.1%	37.3%	17.6%	0%	0%
Alevin	May	Mortality	36.3%	16.6%	7.6%	3.5%	1.6%
Fry	June	Mortality	100%	100%	56.7%	31.7%	17.7%
Parr	All year	TD	0.19	0.017	0.0016	0.0001	0.0000
Wild smolt	May	TD	0.19	0.017	0.0016	0.0001	0.0000
Hatchery Smolt	May 15-25	TD	0.19	0.017	0.0016	0.0001	0.0000

Table 4.1. Probabilities of extinction and of recovery within 1 to 10 decades for the LaHave River (above Morgans Falls) Atlantic salmon population. Two scenarios are shown, one based on the 1980's dynamics (past dynamics) and one based on the 2000's dynamics (present dynamics). The same random numbers are used for each scenario to ensure they are comparable. Probabilities are calculated as the proportion of 2000 Monte Carlo simulations of population trajectories that either became extinct or met the recovery target.

	Probability of Extinction		Probability of Recovery	
Dynamics:	Present	Past	Present	Past
Year				
10	0.00	0.00	0.00	0.34
20	0.05	0.00	0.00	0.97
30	0.31	0.00	0.00	1.00
40	0.66	0.00	0.00	1.00
50	0.87	0.00	0.00	1.00
60	0.96	0.00	0.00	1.00
70	0.99	0.00	0.00	1.00
80	1.00	0.00	0.00	1.00
90	1.00	0.00	0.00	1.00
100	1.00	0.00	0.00	1.00

Table 4.2. Probabilities of extinction and of recovery within 1 to 10 decades for the St. Mary's River (West Branch) Atlantic salmon population. Two scenarios are shown, one based on the 1980's dynamics (past dynamics) and one based on the 2000's dynamics (present dynamics). The same random numbers are used for each scenario to ensure they are comparable. Probabilities are calculated as the proportion of 2000 Monte Carlo simulations of population trajectories that either became extinct or met the recovery target.

	Probability of Extinction		Probability of Recovery	
Dynamics:	Present	Past	Present	Past
Year				
10	0.01	0.00	0.00	0.06
20	0.10	0.00	0.00	0.89
30	0.30	0.00	0.00	0.97
40	0.53	0.00	0.00	0.98
50	0.73	0.00	0.00	0.98
60	0.86	0.00	0.00	0.98
70	0.93	0.00	0.00	0.98
80	0.97	0.00	0.00	0.98
90	0.99	0.00	0.00	0.98
100	0.99	0.00	0.00	0.98

Table 5.1. At-sea mortality rates used in the recovery scenario analyses for the LaHave River (above Morgans Falls) and St. Mary's River (West Branch) Atlantic salmon populations. The intermediate fractions are the proportionate increase in at-sea survival between the past and present scenarios.

		Time Period			
Population	Life History Parameter	Present (2000's)	Intermediate 1/3	Intermediate 2/3	Past (1980's)
LaHave	1SW return rate (%)	2.25	3.92	5.60	7.28
	2SW return rate (%)	0.33	0.47	0.60	0.74
St. Mary's	1SW return rate (%)	1.18	1.90	2.61	3.33
	2SW return rate (%)	0.09	0.31	0.53	0.74
Both	Probability of being an alternate-year repeat spawner	0.963	0.964	0.964	0.965
	Post-spawning instantaneous mortality rate	1.60	1.45	1.30	1.15

Table 5.2. Proportions of 2000 simulated population trajectories that either go extinct or meet the recovery target within 10, 20, 30 and 50 year time horizons based on recovery scenarios for the LaHave River (above Morgans Falls) Atlantic salmon population. The marine scenarios reflect changes from the present levels (2000's) of at-sea survival to those in the past (1980's). The freshwater scenarios reflect increases in freshwater productivity from the present level (one) to two times the present level. The lettering for the runs corresponds to those in Figures 5.1 – 5.3. Extreme event scenarios are the average frequency of extreme events and the reduction in egg to fry survival corresponding to the event.

Run	Marine Scenario	Freshwater Scenario	Extreme Event Scenario	Proportion Extinct				Proportion Recovered			
				10 yr	20 yr	30 yr	50 yr	10 yr	20 yr	30 yr	50 yr
a	present	1	10 yr; 0.2	0.00	0.05	0.31	0.87	0.00	0.00	0.00	0.00
b	present	1.2	10 yr; 0.2	0.00	0.01	0.03	0.21	0.00	0.00	0.00	0.00
c	present	1.5	10 yr; 0.2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
d	present	2	10 yr; 0.2	0.00	0.00	0.00	0.00	0.00	0.01	0.03	0.09
e	present	1.5	20 yr; 0.1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
f	present	1.5	none	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
g	intermediate 1/3	1	10 yr; 0.2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
h	intermediate 1/3	1.2	10 yr; 0.2	0.00	0.00	0.00	0.00	0.00	0.01	0.04	0.10
i	intermediate 1/3	1.5	10 yr; 0.2	0.00	0.00	0.00	0.00	0.01	0.19	0.43	0.62
j	intermediate 1/3	2	10 yr; 0.2	0.00	0.00	0.00	0.00	0.12	0.80	0.95	0.97
k	intermediate 1/3	1.5	20 yr; 0.1	0.00	0.00	0.00	0.00	0.01	0.24	0.53	0.73
l	intermediate 1/3	1.5	none	0.00	0.00	0.00	0.00	0.01	0.32	0.66	0.83
m	intermediate 2/3	1	10 yr; 0.2	0.00	0.00	0.00	0.00	0.00	0.12	0.34	0.53
n	intermediate 2/3	1.2	10 yr; 0.2	0.00	0.00	0.00	0.00	0.03	0.49	0.78	0.89
o	intermediate 2/3	1.5	10 yr; 0.2	0.00	0.00	0.00	0.00	0.21	0.90	0.99	0.99
p	intermediate 2/3	2	10 yr; 0.2	0.00	0.00	0.00	0.00	0.68	1.00	1.00	1.00
q	intermediate 2/3	1.5	20 yr; 0.1	0.00	0.00	0.00	0.00	0.24	0.94	1.00	1.00
r	intermediate 2/3	1.5	none	0.00	0.00	0.00	0.00	0.27	0.98	1.00	1.00
s	past	1	10 yr; 0.2	0.00	0.00	0.00	0.00	0.09	0.74	0.94	0.97
t	past	1.2	10 yr; 0.2	0.00	0.00	0.00	0.00	0.24	0.92	0.99	1.00
u	past	1.5	10 yr; 0.2	0.00	0.00	0.00	0.00	0.69	1.00	1.00	1.00
v	past	2	10 yr; 0.2	0.00	0.00	0.00	0.00	0.96	1.00	1.00	1.00
w	past	1.5	20 yr; 0.1	0.00	0.00	0.00	0.00	0.75	1.00	1.00	1.00
x	past	1.5	none	0.00	0.00	0.00	0.00	0.72	1.00	1.00	1.00

Table 5.3. Proportions of 2000 simulated population trajectories that either go extinct or meet the recovery target within 10, 20, 30 and 50 year time horizons based on recovery scenarios for the St. Mary's River (West Branch) Atlantic salmon population. The marine scenarios reflect changes from the present levels (2000's) of at-sea survival to those in the past (1980's). The freshwater scenarios reflect increases in freshwater productivity from the present level (one) to two times the present level. The lettering for the runs corresponds to those in Figures 5.4 – 5.6. Extreme event scenarios are the average frequency of extreme events and the reduction in egg to fry survival corresponding to the event.

	Marine	Freshwater	Extreme Event	Proportion Extinct				Proportion Recovered			
Run	Scenario	Scenario	Scenario	10 yr	20 yr	30 yr	50 yr	10 yr	20 yr	30 yr	50 yr
a	present	1	10 yr; 0.2	0.01	0.11	0.31	0.74	0.00	0.00	0.00	0.00
b	present	1.2	10 yr; 0.2	0.00	0.01	0.04	0.12	0.00	0.00	0.00	0.00
c	present	1.5	10 yr; 0.2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
d	present	2	10 yr; 0.2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
e	present	1.5	20 yr; 0.1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
f	present	1.5	none	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
g	intermediate 1/3	1	10 yr; 0.2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
h	intermediate 1/3	1.2	10 yr; 0.2	0.00	0.00	0.00	0.00	0.00	0.01	0.04	0.10
i	intermediate 1/3	1.5	10 yr; 0.2	0.00	0.00	0.00	0.00	0.00	0.17	0.38	0.49
j	intermediate 1/3	2	10 yr; 0.2	0.00	0.00	0.00	0.00	0.04	0.77	0.91	0.93
k	intermediate 1/3	1.5	20 yr; 0.1	0.00	0.00	0.00	0.00	0.00	0.22	0.47	0.57
l	intermediate 1/3	1.5	none	0.00	0.00	0.00	0.00	0.00	0.29	0.56	0.65
m	intermediate 2/3	1	10 yr; 0.2	0.00	0.00	0.00	0.00	0.00	0.20	0.44	0.56
n	intermediate 2/3	1.2	10 yr; 0.2	0.00	0.00	0.00	0.00	0.01	0.60	0.83	0.87
o	intermediate 2/3	1.5	10 yr; 0.2	0.00	0.00	0.00	0.00	0.13	0.95	0.98	0.99
p	intermediate 2/3	2	10 yr; 0.2	0.00	0.00	0.00	0.00	0.63	1.00	1.00	1.00
q	intermediate 2/3	1.5	20 yr; 0.1	0.00	0.00	0.00	0.00	0.15	0.97	0.99	1.00
r	intermediate 2/3	1.5	none	0.00	0.00	0.00	0.00	0.17	0.99	1.00	1.00
s	past	1	10 yr; 0.2	0.00	0.00	0.00	0.00	0.07	0.89	0.97	0.98
t	past	1.2	10 yr; 0.2	0.00	0.00	0.00	0.00	0.30	0.99	1.00	1.00
u	past	1.5	10 yr; 0.2	0.00	0.00	0.00	0.00	0.73	1.00	1.00	1.00
v	past	2	10 yr; 0.2	0.00	0.00	0.00	0.00	0.97	1.00	1.00	1.00
w	past	1.5	20 yr; 0.1	0.00	0.00	0.00	0.00	0.79	1.00	1.00	1.00
x	past	1.5	none	0.00	0.00	0.00	0.00	0.84	1.00	1.00	1.00

10. FIGURES

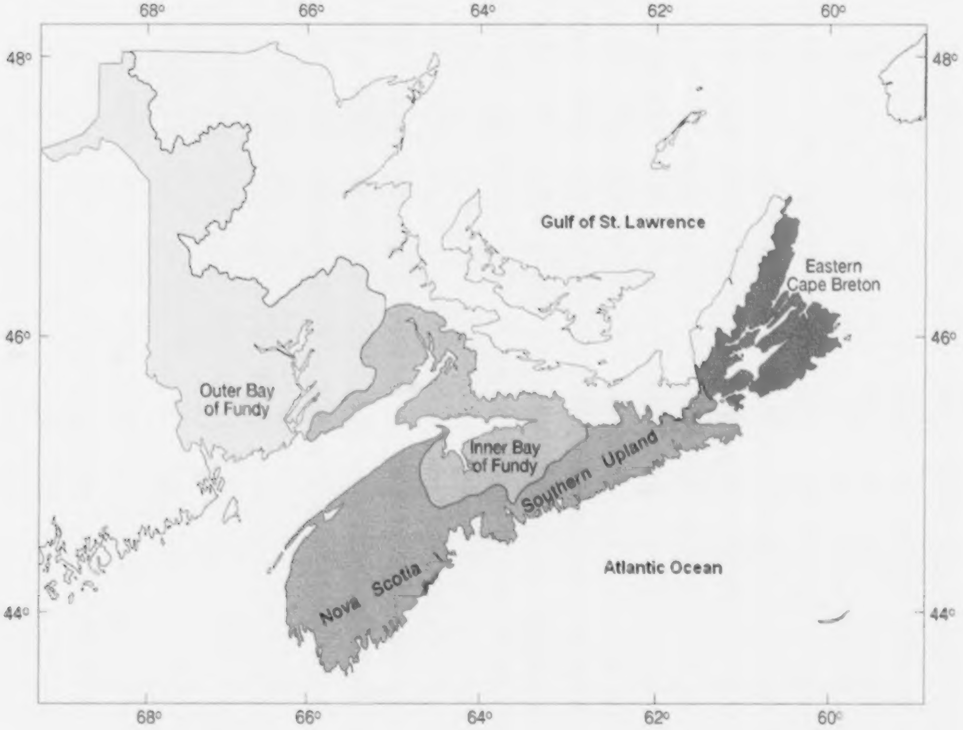
68°
66°
64°
62°
60°
48°
46°
44°
Gulf of St. Lawrence
Eastern Cape Breton
Outer Bay of Fundy
Inner Bay of Fundy
Southern Upland
Nova Scotia
Atlantic Ocean

Figure 1. Map showing the location of the Southern Upland relative to the three other designatable units for Atlantic salmon in the Maritimes.

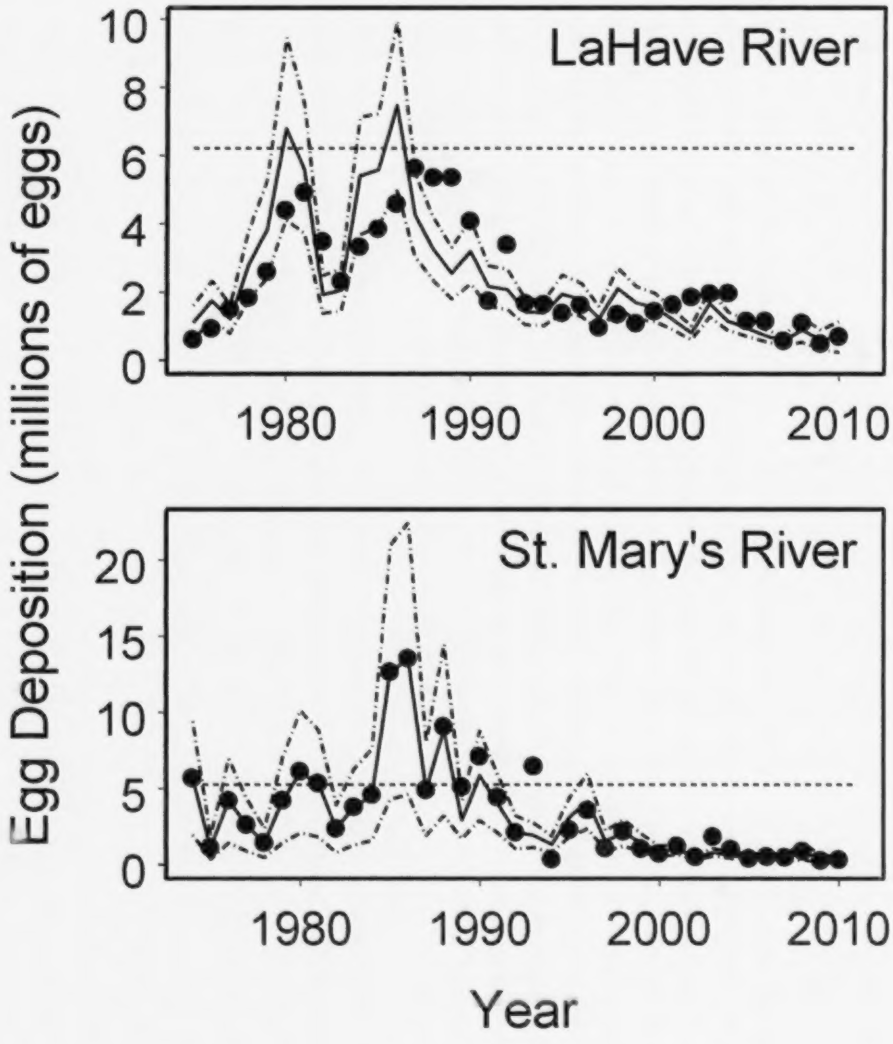

Figure 2.2.1. Observed (points) and fitted (lines) egg depositions for the Atlantic salmon populations in the LaHave River (above Morgans Falls) and the West Branch of the St. Mary's River from 1974 to 2010 as estimated with the life history model. The broken lines show 95% confidence intervals based on normal approximations. The horizontal dashed lines are the conservation requirement for each population.

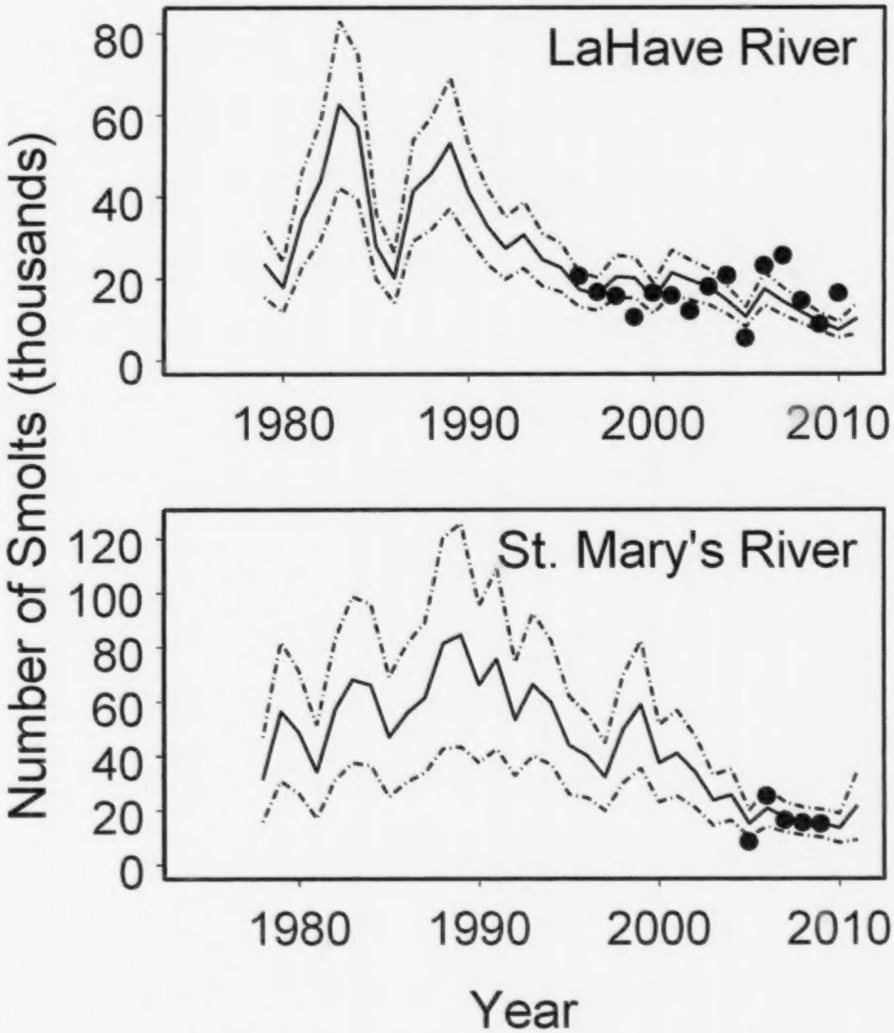

Figure 2.2.2. Observed (points) and estimated (lines) wild smolt production for the Atlantic salmon populations in the LaHave River (above Morgans Falls) and the West Branch of the St. Mary's River from 1978 to 2011 as estimated with the life history model. The broken lines show 95% confidence intervals based on normal approximations.

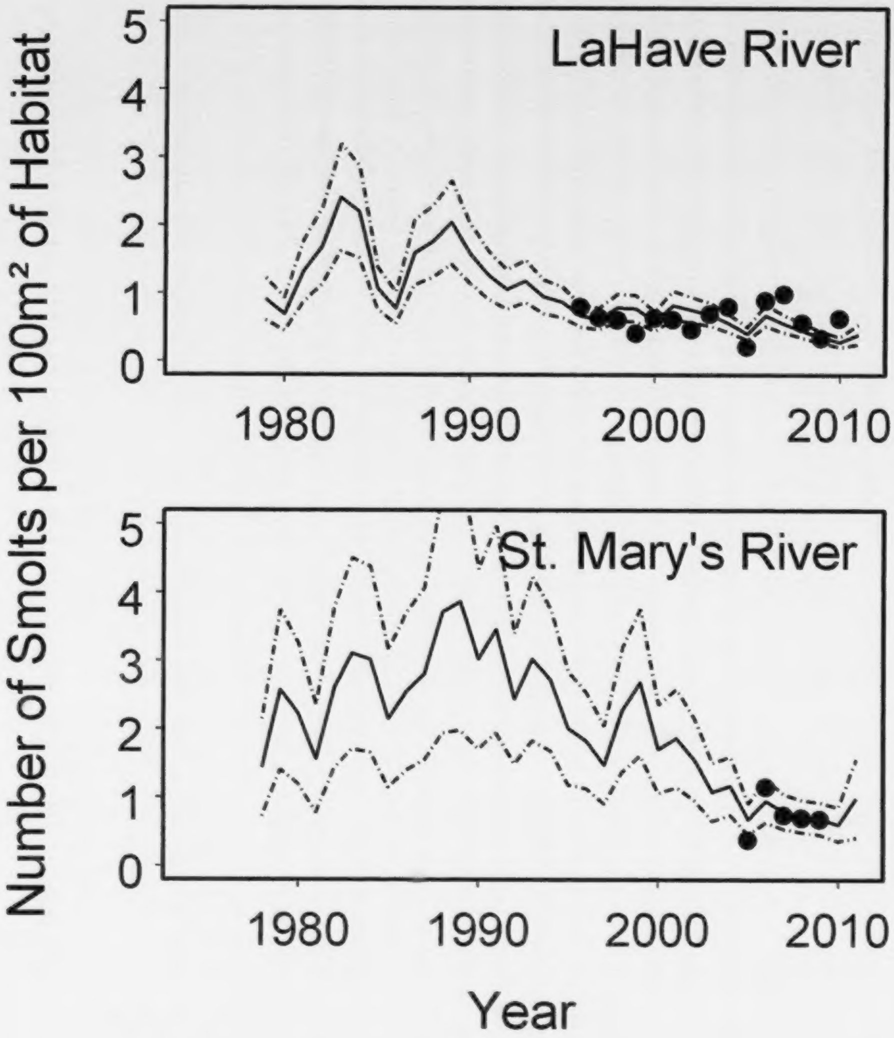

Figure 2.2.3. Observed (points) and estimated (lines) wild smolt production for the Atlantic salmon populations in the LaHave River (above Morgans Falls) and the West Branch of the St. Mary's River from 1978 to 2011, standardized by habitat area, as estimated with the life history model. The broken lines show 95% confidence intervals based on normal approximations.

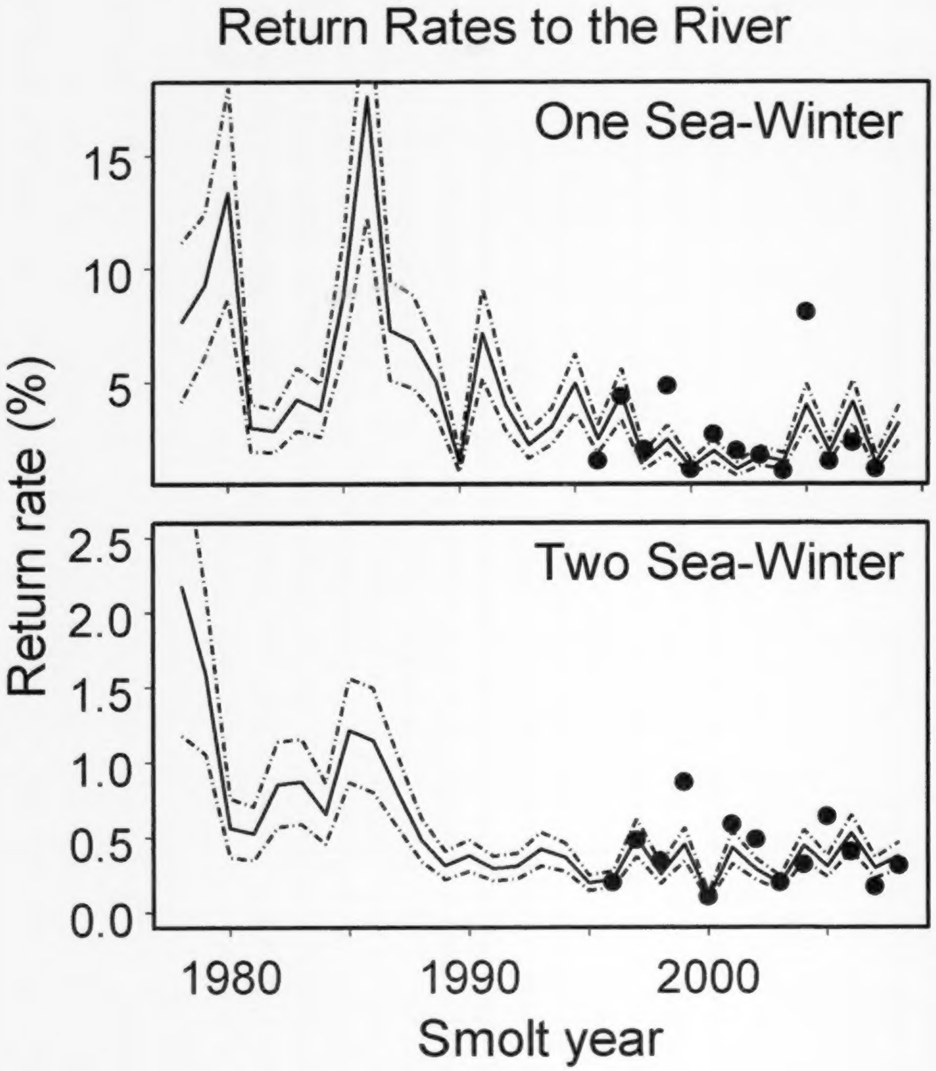

Figure 2.2.4. Observed (points) and estimated (lines) return rates for 1SW and 2SW wild Atlantic salmon for the LaHave River (above Morgans Falls) population, as estimated with the life history model. The broken lines show 95% confidence intervals based on normal approximations. Return rates are to the mouth of the river (are corrected for removals by the recreational fishery).

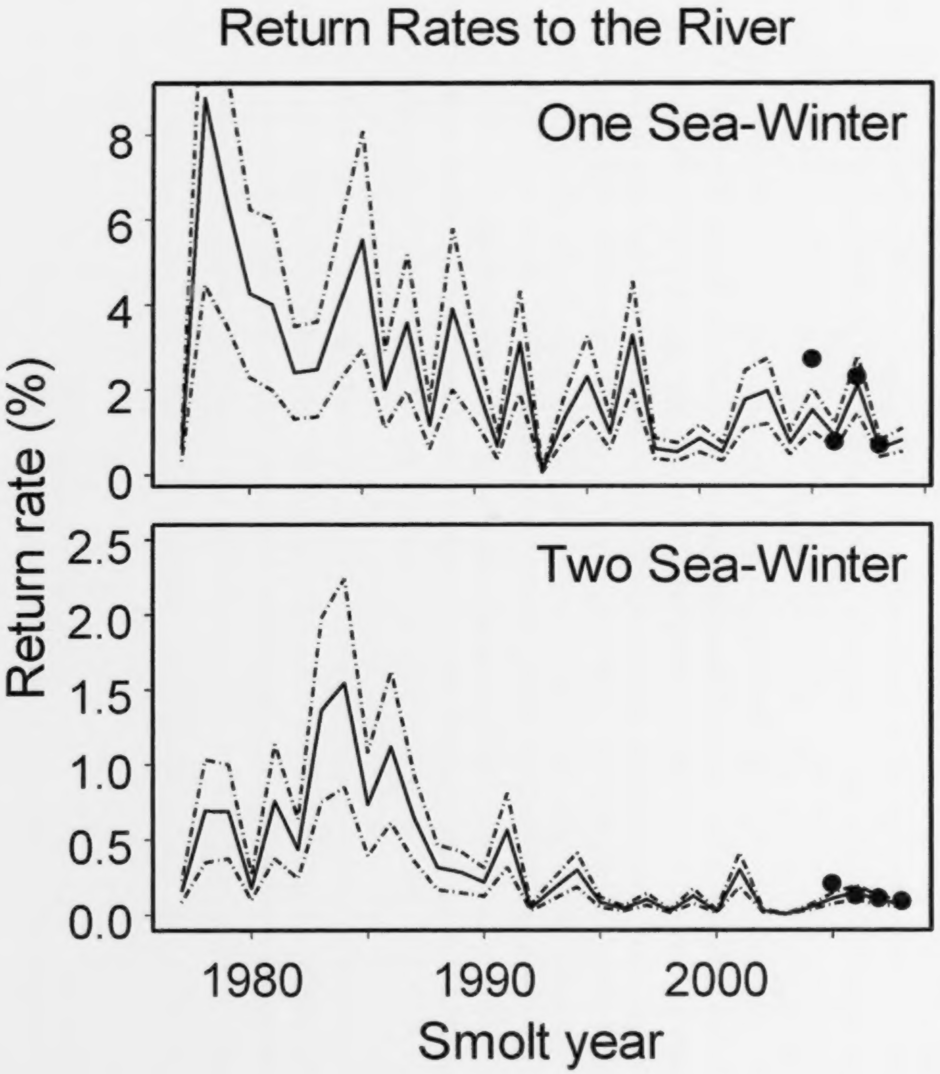

Figure 2.2.5. Observed (points) and estimated (lines) return rates for 1SW and 2SW wild Atlantic salmon for the West Branch of the St. Mary's River population, as estimated with the life history model. The broken lines show 95% confidence intervals based on normal approximations. Return rates are to the mouth of the river (are corrected for removals by the recreational fishery).

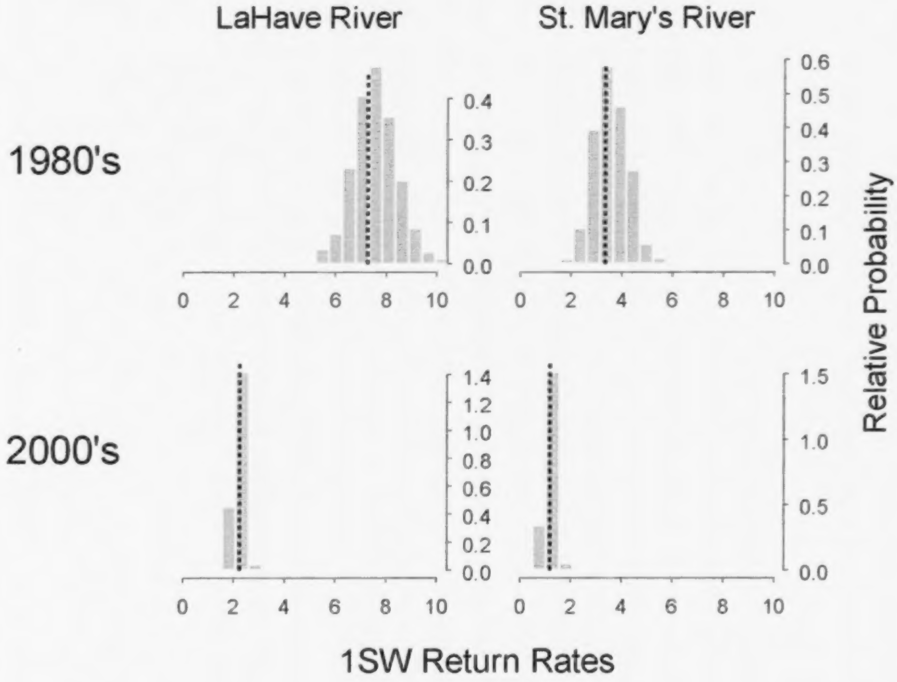

Figure 2.2.6. Bayesian posterior probability densities for the average return rates of 1SW wild Atlantic salmon for the 1980's (top row) and 2000's (bottom row) for the populations in the Lahave River (above Morgans Falls) and in the West Branch of the St. Mary's River. The vertical dashed lines show the maximum likelihood estimates from the model. The return rates are as estimated to the mouth of the river. The time periods refer to the years of smolt production.

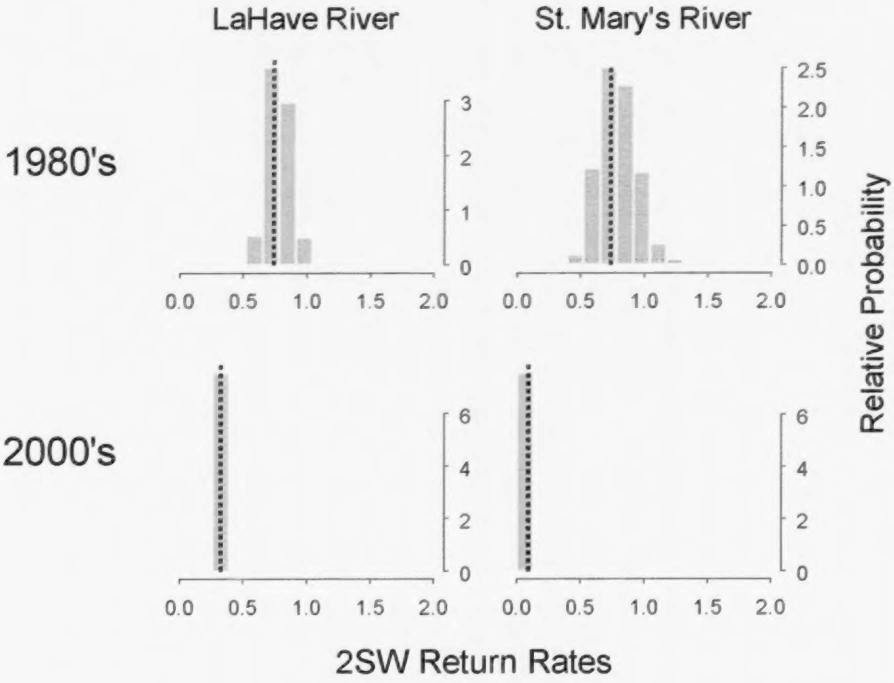

Figure 2.2.7. Bayesian posterior probability densities for the average return rates of 2SW wild Atlantic salmon during the 1980's (top row) and 2000's (bottom row) for the populations in the Lahave River (above Morgans Falls – left column) and in the West Branch of the St. Mary's River (right column). The vertical dashed lines show the maximum likelihood estimates from the model. The return rates are as estimated to the mouth of the river. The time periods refer to the years of smolt production.

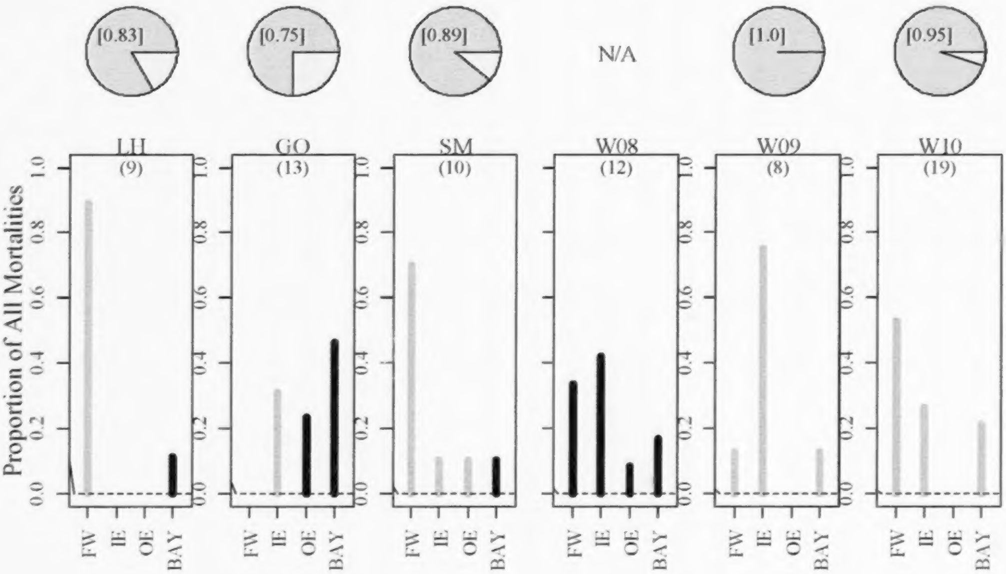

Figure 2.3.1. Proportion of all mortalities within each habitat-zone estimated during an acoustic tracking study for smolt in four Southern Upland rivers. Sample size in parentheses () indicate all mortalities occurring within areas where active tracking occurred. Grey lines represent habitat-zones examined via active tracking and black lines represent zones where active tracking did not occur. Pie charts indicate the proportion [] of all mortalities for which the tags were not found via active tracking (i.e. disappeared). LH = Lahave River, GO = Gold River, SM = St. Mary's River, W08 = West River 2008, W09 = West River 2009 and W10 = West River 2010. FW = freshwater, IE = inner estuary, OE = outer estuary and BAY = bay habitats. From Halfyard et al. (2012).

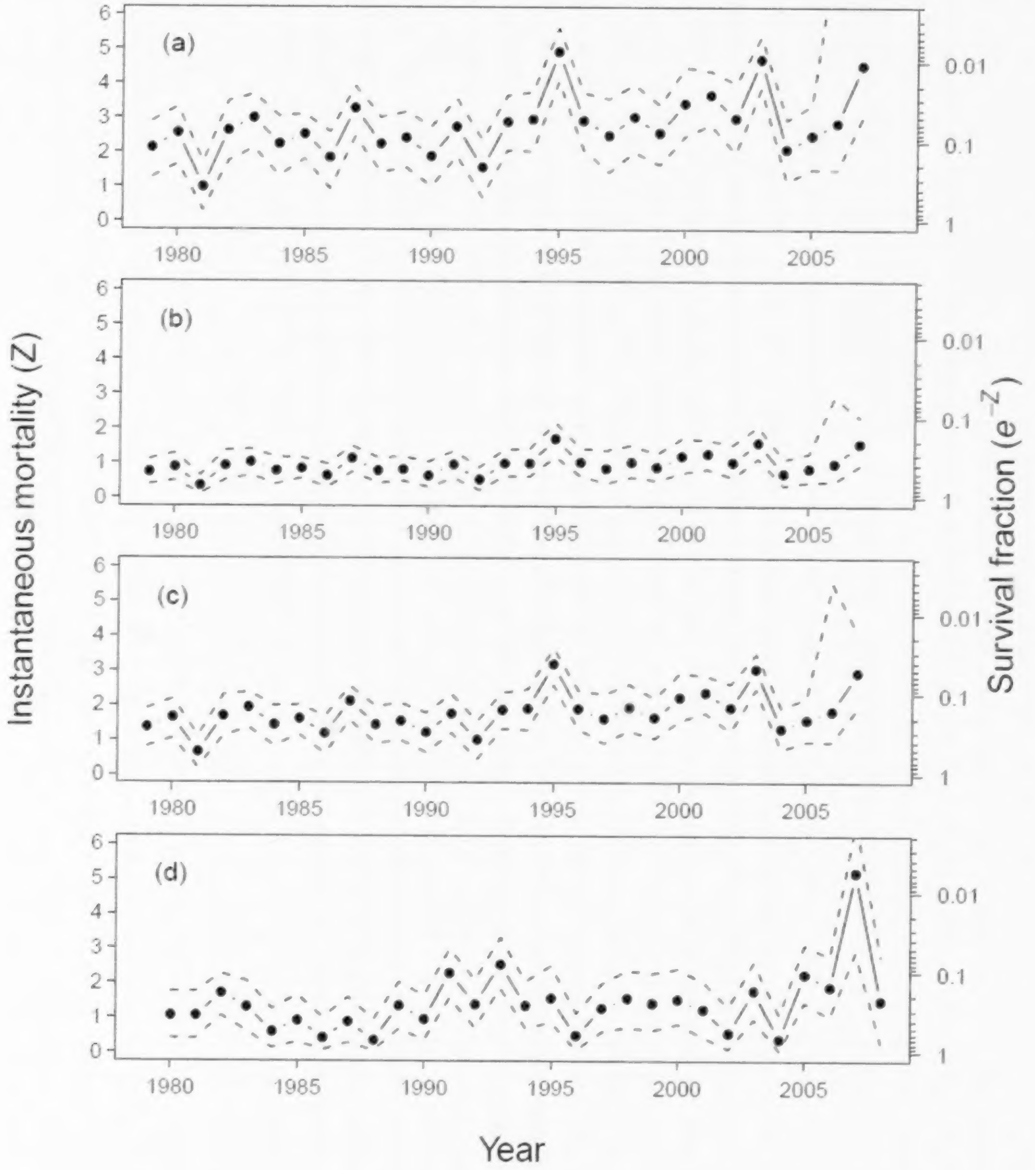

Figure 2.4.1. Model estimates of the instantaneous mortality parameters and the resulting annual survival fraction for repeat spawning Atlantic salmon from the LaHave River (above Morgans Falls). Broken lines represent the 80% credible intervals. The different mortality parameters are: first year mature mortality for male 1SW (a), first year mature mortality for male 2SW (b), first year mature mortality for female 1SW and 2SW (c), and second year mature mortality for alternate spawners (d). From Hubley and Gibson (2011).

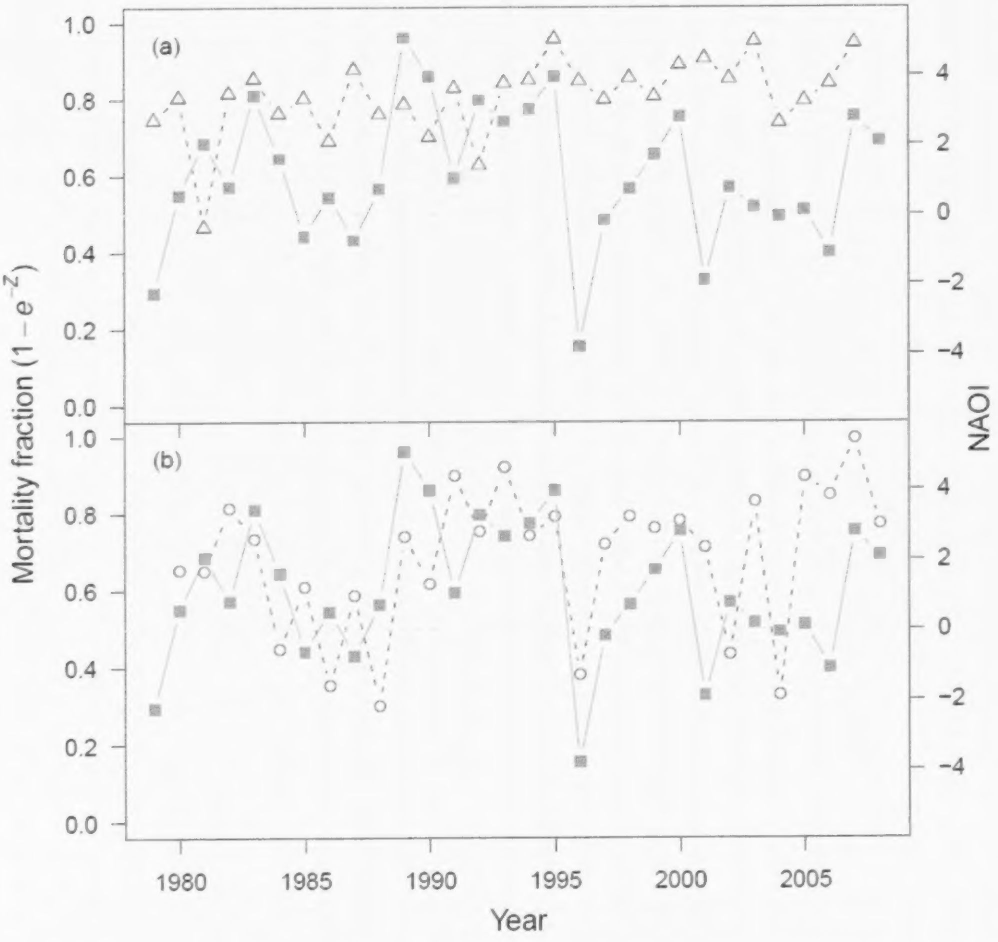

Figure 2.4.2. Annual mortality rate as the proportion of potential mature Atlantic salmon from the LaHave River (above Morgans Falls) that die in a given first year plotted alongside the winter North Atlantic Oscillation Index (■), an environmental variable thought to influence the marine ecology of Atlantic salmon. The NAOI is compared to mortality in the first year (Δ) which occurs mainly in freshwater (a) and mortality in the second year (○) which occurs mainly in the marine environment (b). A horizontal dashed line is provided for reference and represents an NAOI of 0 or an annually mortality rate of 50%. From Hubley and Gibson (2011).

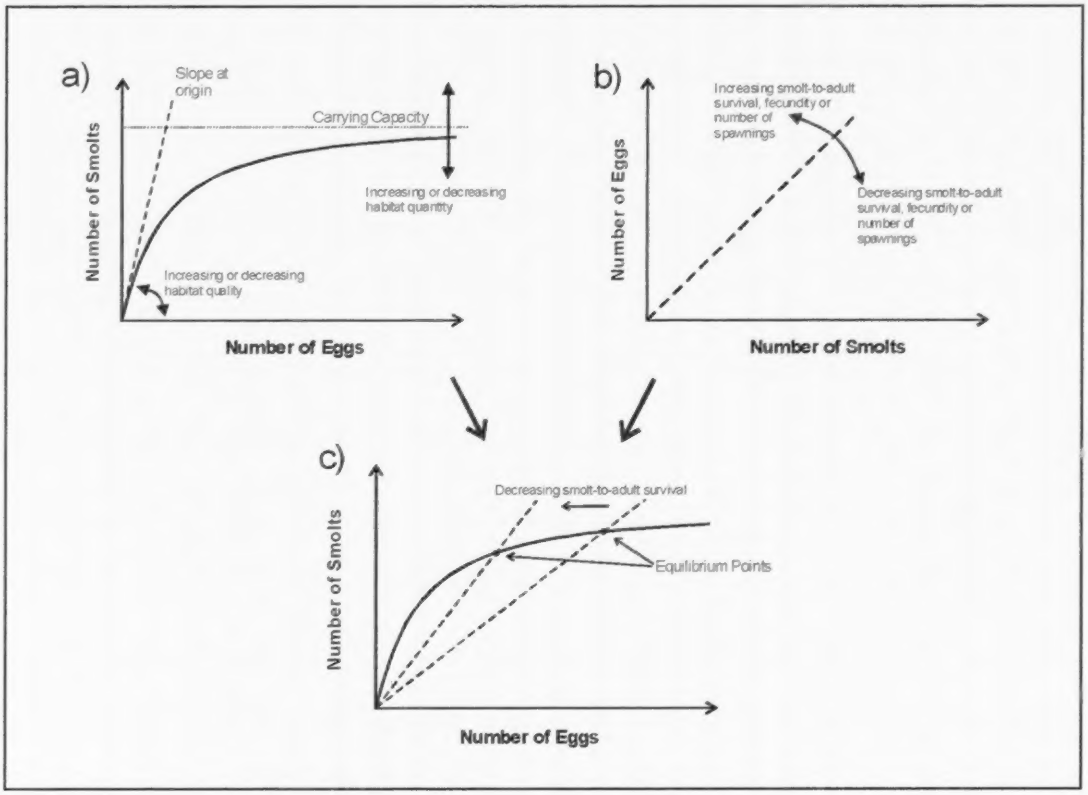
a)
Slope at origin
Carrying Capacity
Increasing or decreasing habitat quantity
Increasing or decreasing habitat quality
Number of Smolts
Number of Eggs
b)
Increasing smolt-to-adult survival, fecundity or number of spawnings
Decreasing smolt-to-adult survival, fecundity or number of spawnings
Number of Eggs
Number of Smolts
c)
Decreasing smolt-to-adult survival
Equilibrium Points
Number of Smolts
Number of Eggs

Figure 2.5.1. Conceptual diagram showing how an equilibrium model can be used to analyze the dynamics of a fish population and to determine how a population will respond to either changes in life history parameter values or recovery actions. A Beverton-Holt model (a) is used to model the density-dependent relationship for survival from eggs to smolt. The slope at the origin of this model, which is the maximum number of smolts produced per egg in the absence of density dependent effects, changes as habitat quality changes, whereas changes in the amount of habitat changes the carrying capacity. The number of eggs produced per smolt throughout its life (b) changes with smolt-to-adult survival, fecundity, age-at-maturity or the number of times a fish spawns throughout its life. The population equilibrium (c) occurs at the population size where the production of smolts by eggs is equal to the production of eggs by smolts throughout their lives, and is the size at which the population will stabilize if all life history rates and the habitat carrying capacity remain unchanged. The population equilibrium changes as the values of the life history parameters change (from Gibson and Amiro 2007).

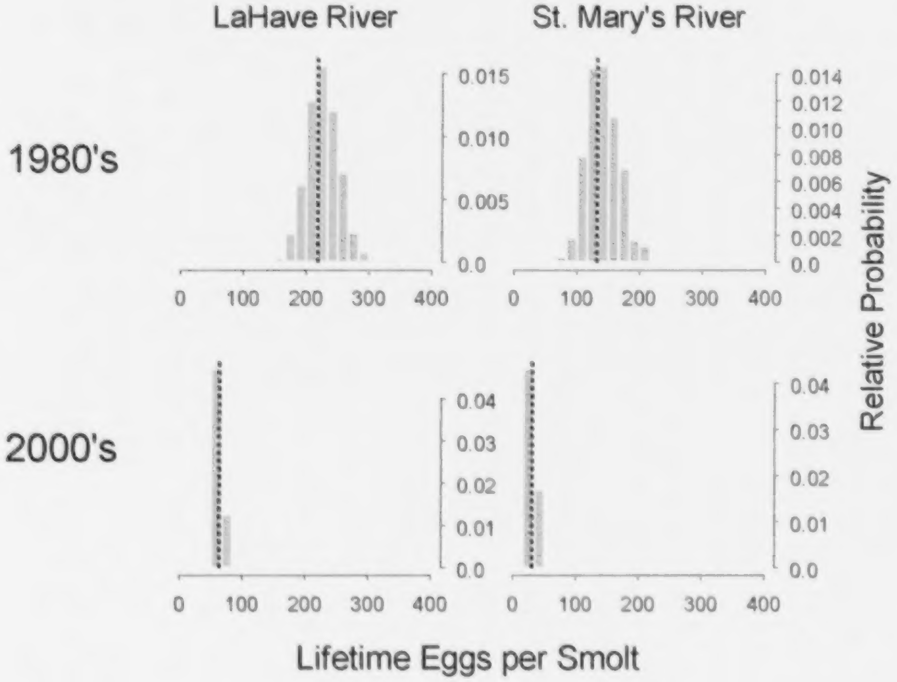

Figure 2.5.2. Bayesian posterior probability densities for the average numbers of eggs produced by a smolt throughout its life for wild Atlantic salmon during the 1980's (top row) and 2000's (bottom row) for the populations in the LaHave River (above Morgans Falls) and in the West Branch of the St. Mary's River. The vertical dashed lines show the maximum likelihood estimates from the model. The return rates are as estimated to the mouth of the river. The time periods refer to the years of smolt production.

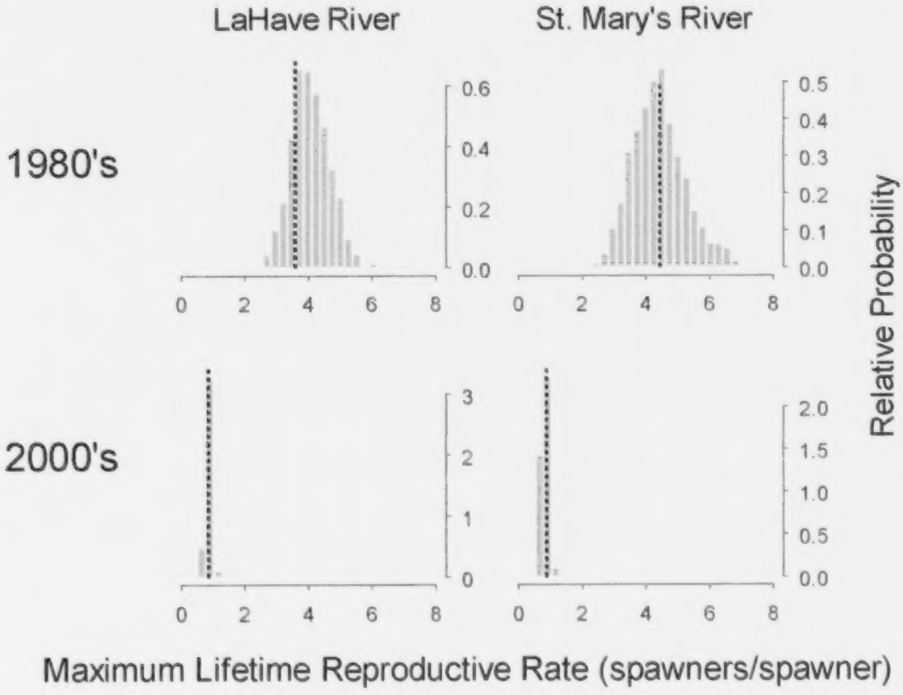

Figure 2.5.3. Bayesian posterior probability densities for the average maximum lifetime reproductive rates for wild Atlantic salmon during the 1980's (top row) and 2000's (bottom row) for the populations in the LaHave River (above Morgans Falls) and in the West Branch of the St. Mary's River. The vertical dashed lines show the maximum likelihood estimates from the model. The return rates are as estimated to the mouth of the river. The time periods refer to the years of smolt production.

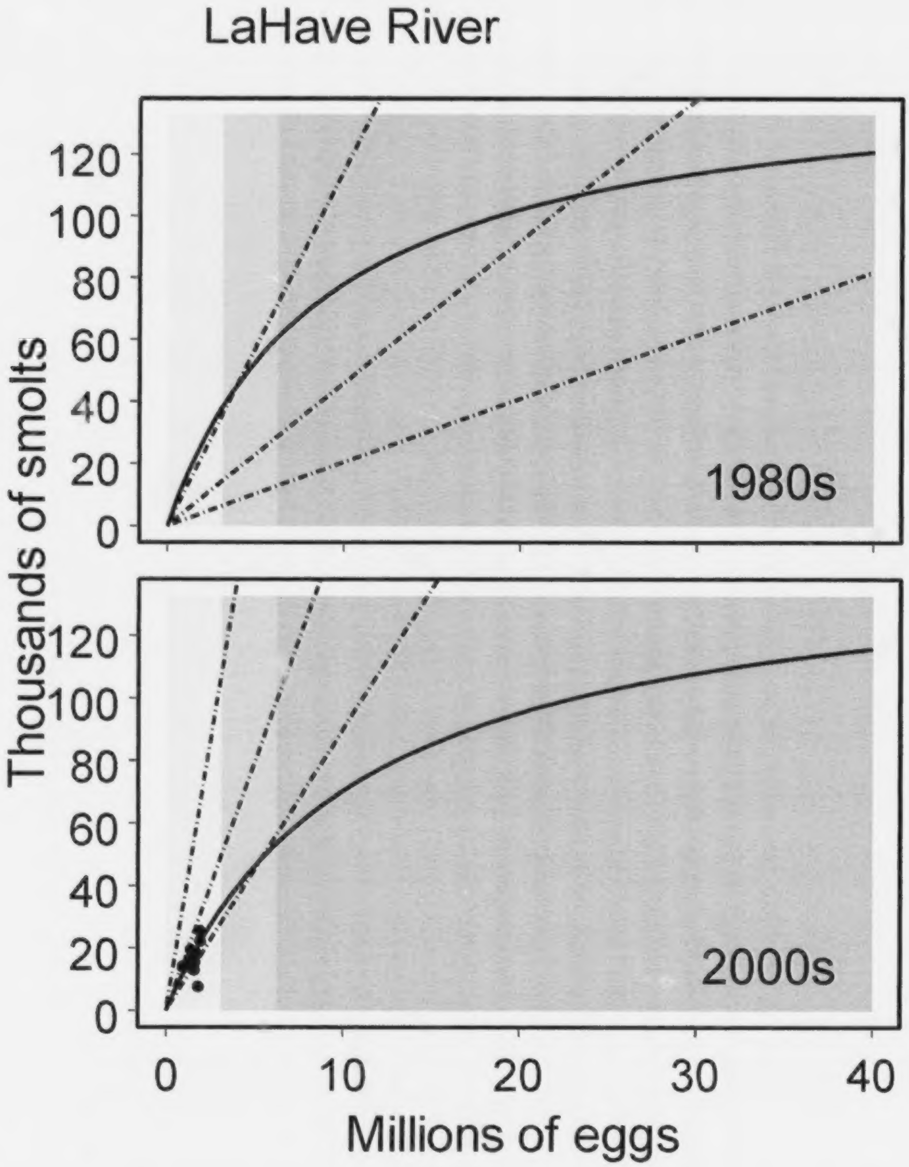

Figure 2.5.4. Equilibrium analysis of the dynamics of the Atlantic salmon population in the LaHave River, above Morgan Falls. The points are the observed egg depositions and smolt production for the 2000 to 2008 (lower panel) egg deposition years. The curved, solid line represents freshwater production. The straight, dashed lines represent marine production as calculated at the minimum observed return rates, the mean observed return rates, and the maximum observed return rates for 1SW and 2SW adults during the two time periods. Dark shading indicates egg depositions above the conservation egg requirement, medium shading is between 50% and 100% the egg requirement, and the light shading is below 50% of the requirement.

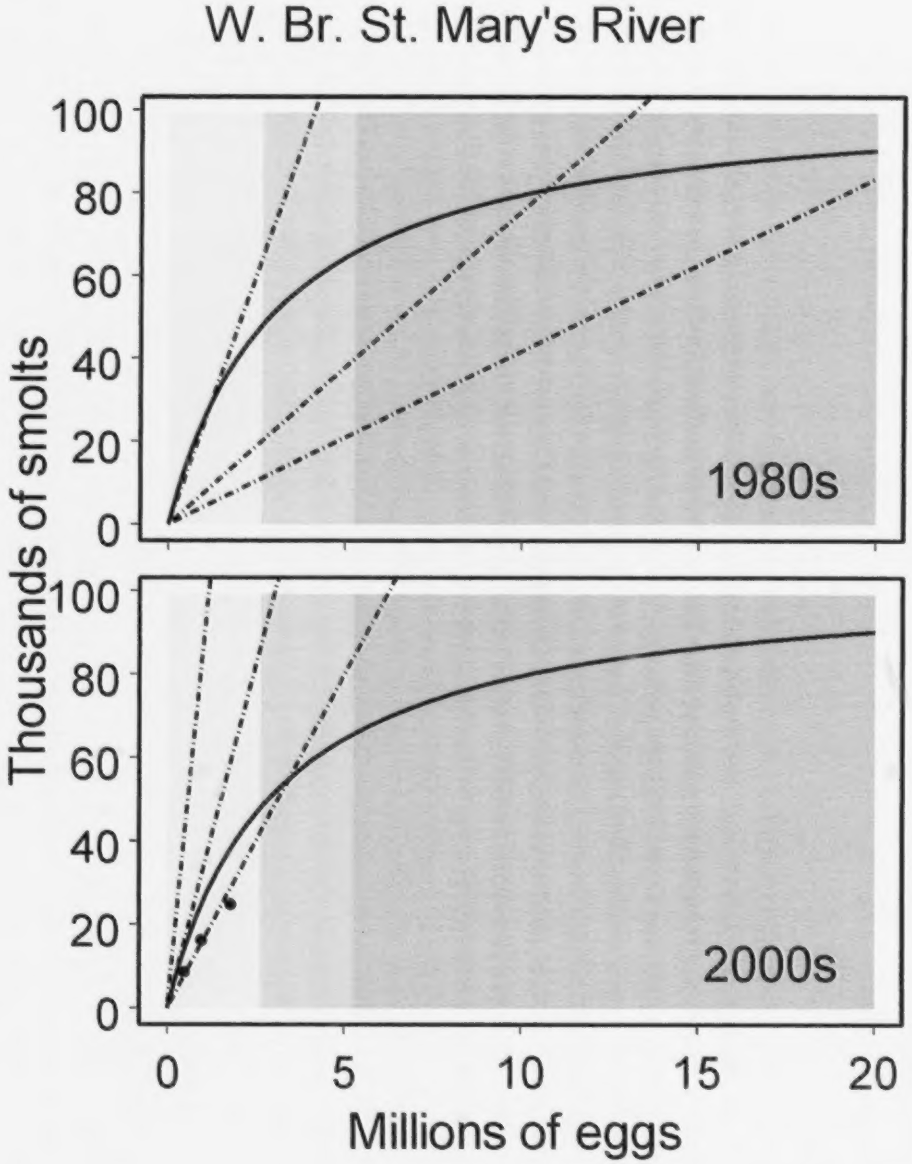

Figure 2.5.5. Equilibrium analysis of the dynamics of the Atlantic salmon population in the West Branch of the St. Mary's River. The points are the observed egg depositions and smolt production for the 2000 to 2008 (lower panel) egg deposition years. The curved, solid line represents freshwater production. The straight, dashed lines represent marine production as calculated at the minimum observed return rates, the mean observed return rates, and the maximum observed return rates for 1SW and 2SW adults during the two time periods. Dark shading indicates egg depositions above the conservation egg requirement, medium shading is between 50% and 100% the egg requirement, and the light shading is below 50% of the requirement.

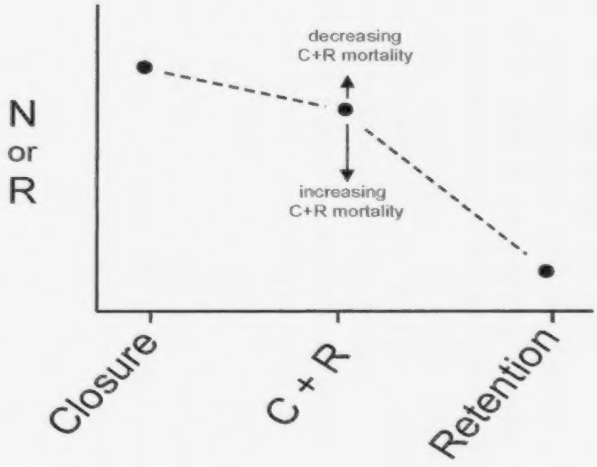
N
or
R
decreasing
C+R mortality
increasing
C+R mortality
Closure
C + R
Retention

Figure 3.1. Schematic representation of the effect of catch and release mortality on population size (N) and population growth rate (R) relative to fishery closures or full retention fisheries (from ICES 2009).

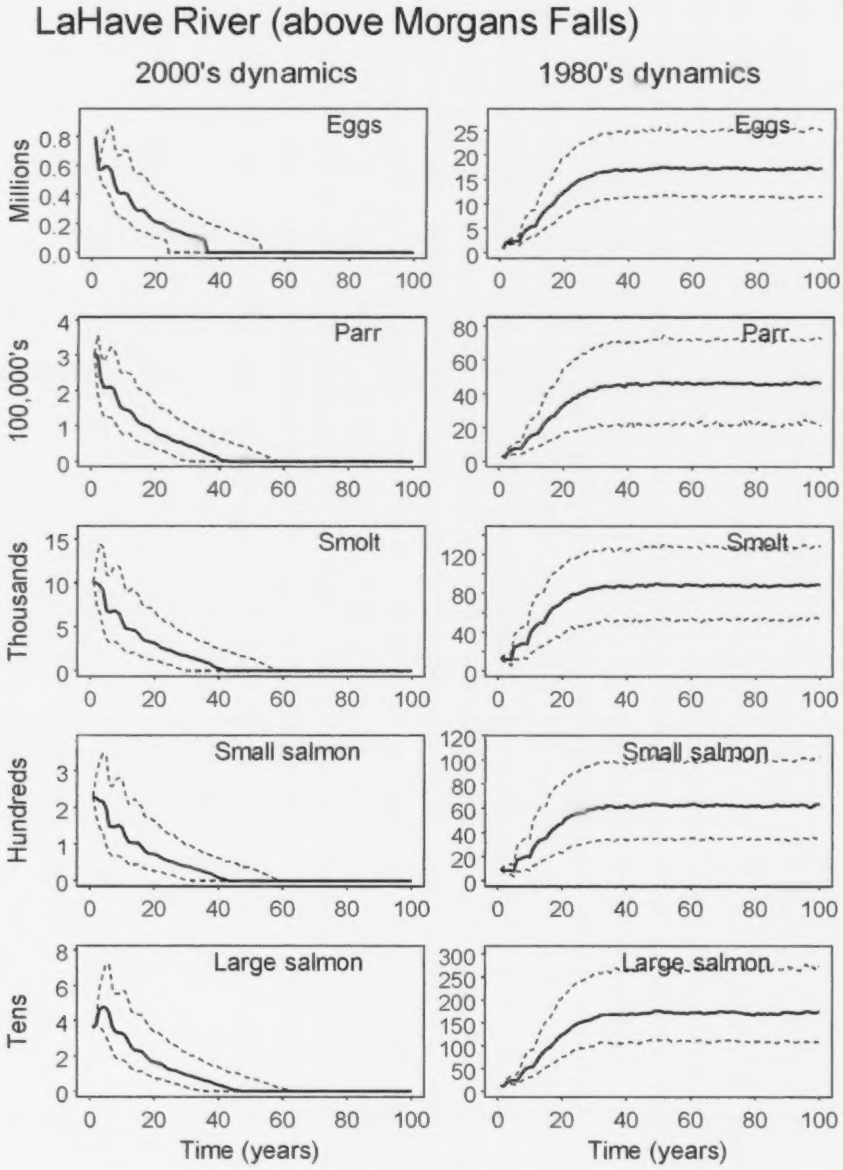

Figure 4.1. Simulated median abundance (solid line) with the 10th and 90th percentiles (dashed lines) for each of five life stages from Monte Carlo simulations of the LaHave River (above Morgans Falls) Atlantic salmon population viability model. Two scenarios are shown, one based on the 1980's dynamics (right panels) and one based on the 2000's dynamics (left panels). The graphs summarize 2000 simulations for each scenario.

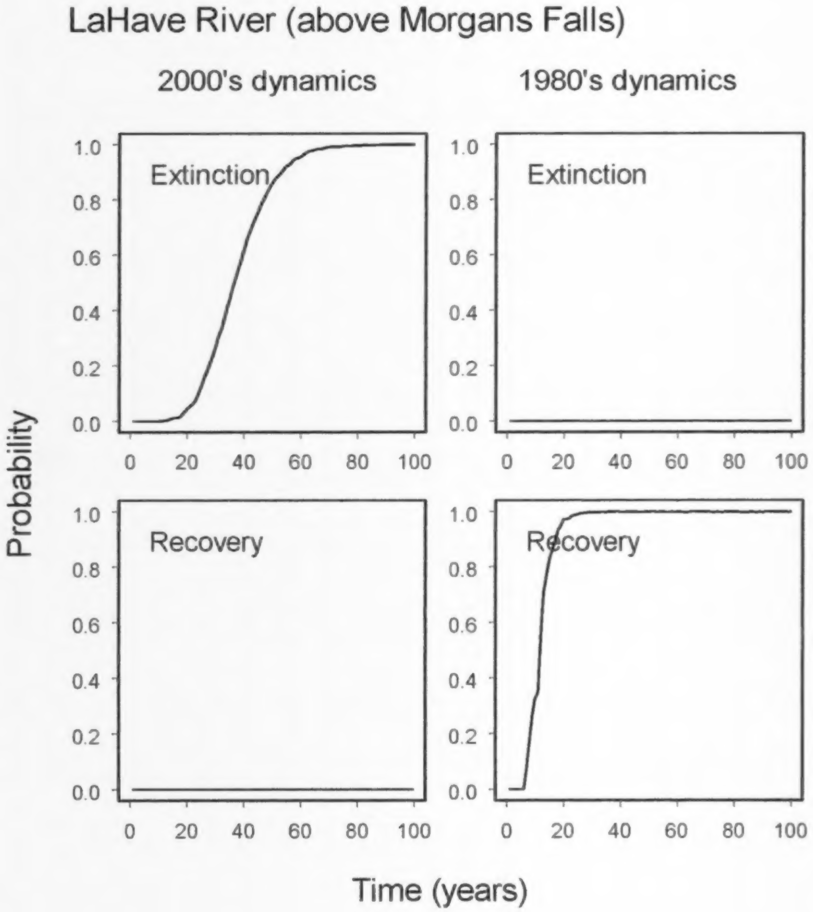

Figure 4.2. The probability of extinction and the probability of recovery as a function of time for the LaHave River (above Morgans Falls) Atlantic salmon population. Two scenarios are shown, one based on the 1980's dynamics (right panels) and one based on the 2000's dynamics (left panels). Probabilities are calculated as the proportion of 2000 Monte Carlo simulations of population trajectories that either went extinct or met the recovery target.

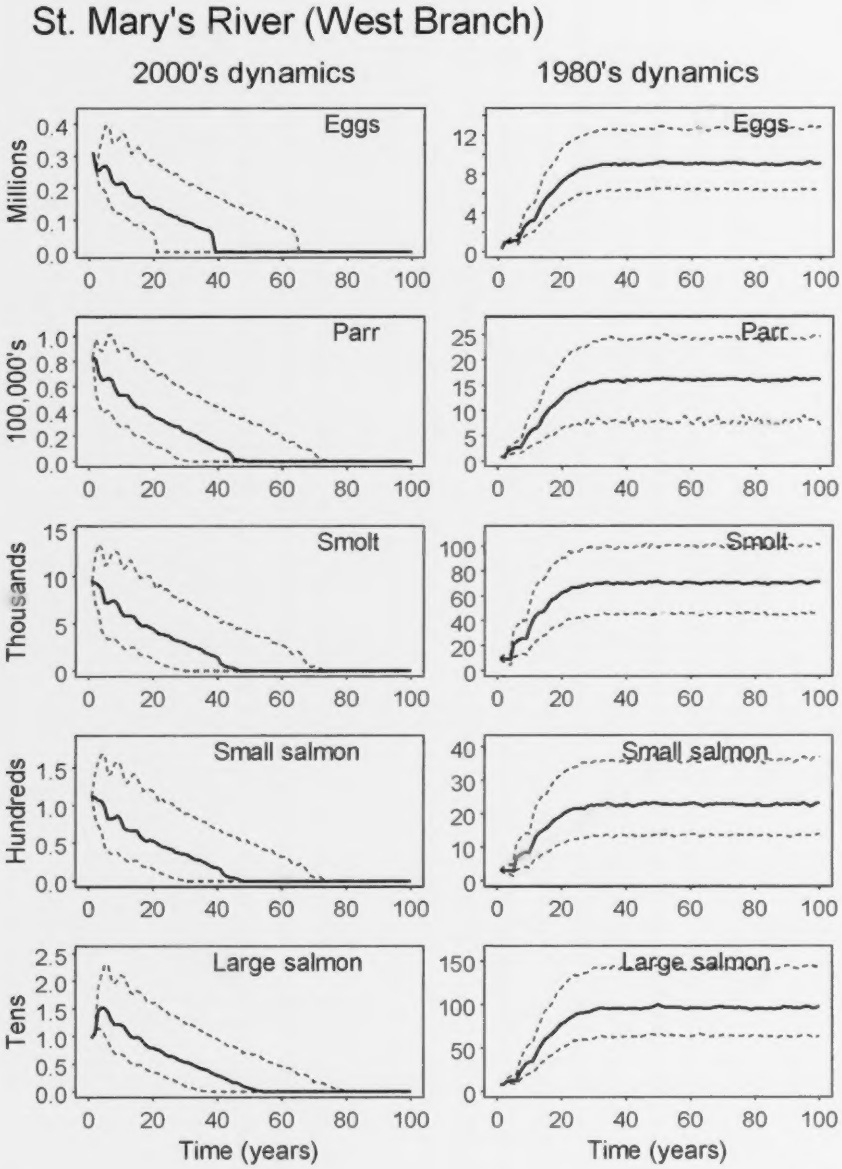

Figure 4.3. Simulated median abundance (solid line) with the 10th and 90th percentiles (dashed lines) for each of five life stages from Monte Carlo simulations of the St. Mary's River (West Branch) Atlantic salmon population viability model. Two scenarios are shown, one based on the 1980's dynamics (right panels) and one based on the 2000's dynamics (left panels). The graphs summarize 2000 simulations for each scenario.

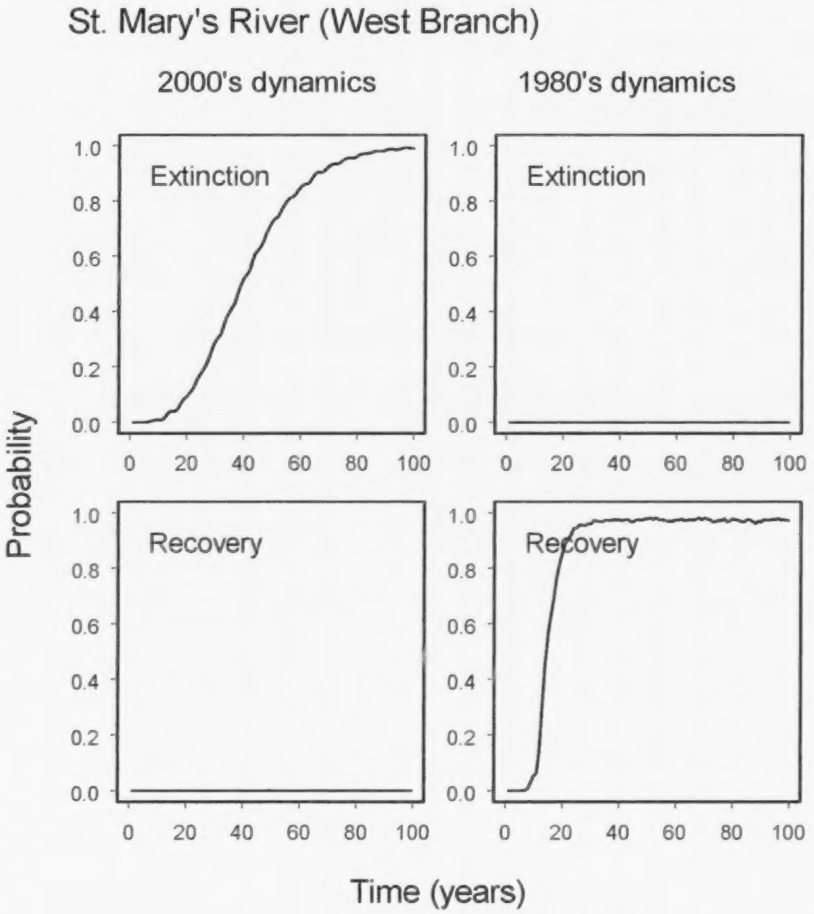

Figure 4.4. The probability of extinction and the probability of recovery as a function of time for the St. Mary's River (West Branch) Atlantic salmon population. Two scenarios are shown, one based on the 1980's dynamics (right panels) and one based on the 2000's dynamics (left panels). Probabilities are calculated as the proportion of 2000 Monte Carlo simulations of population trajectories that either went extinct or met the recovery target.

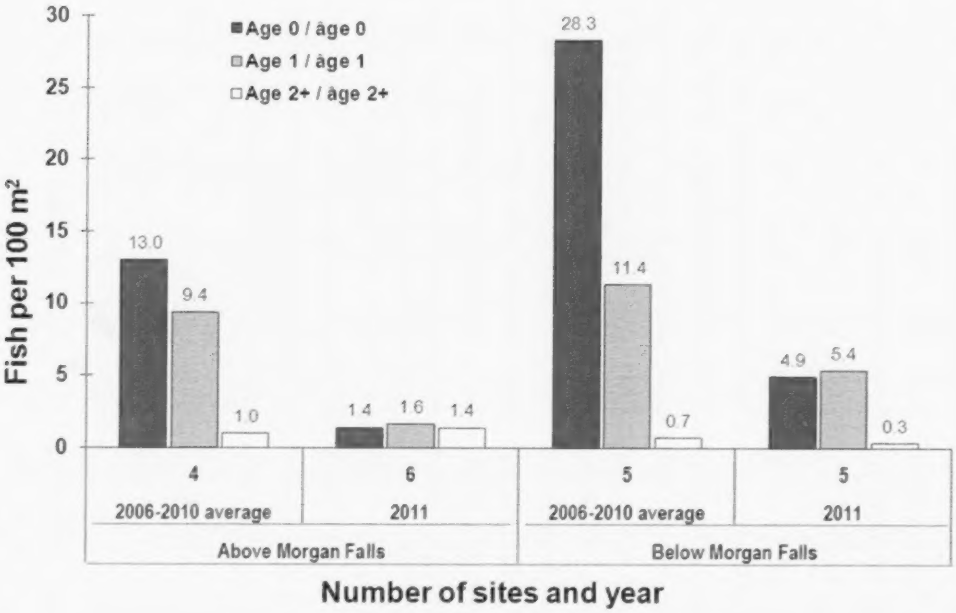

Figure 4.5. Mean density for the three age classes of juvenile salmon (age-0, age-1, and age-2+) above and below Morgan Falls on the LaHave River in 2011 compared to the past five-year average 2006-2010. The number of sampling sites on which the mean is based is listed immediately below the x-axis (from DFO 2012).

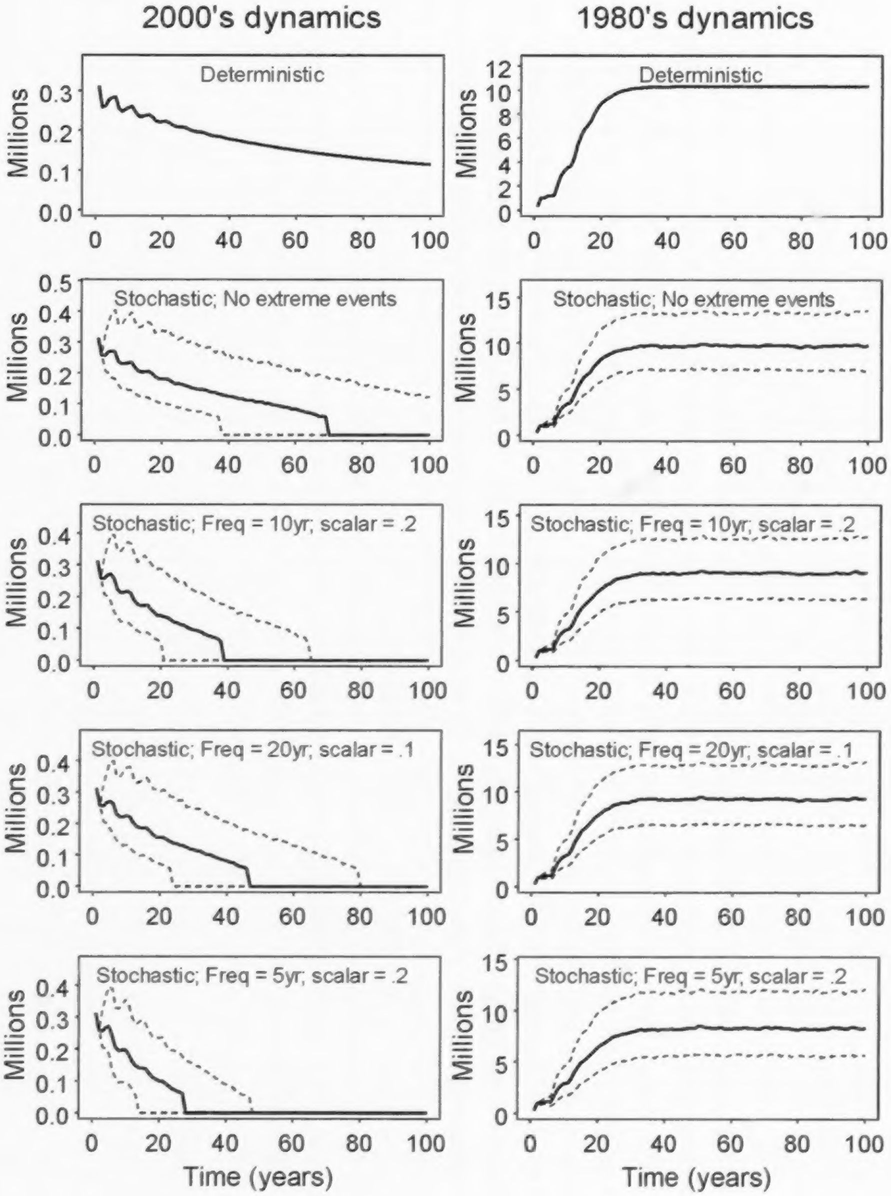

Figure 4.6. Sensitivity analysis of the effects of extreme events on the viability of St. Mary's River (West Branch) Atlantic salmon. The graphs summarize 2000 simulations for each scenario. The median abundance (solid line), and the 10th and 90th percentiles (dashed lines) are shown. Panels on the right and left are based on the 1980's dynamics and 2000's dynamics, respectively. The top row shows a deterministic run without extreme events, the second row a stochastic run without extreme events, the third row a stochastic run with extreme events (the base model), the fourth row the effect of decreasing the frequency and increasing the magnitude of extreme events, and the bottom row the effect of increasing the frequency of extreme events.

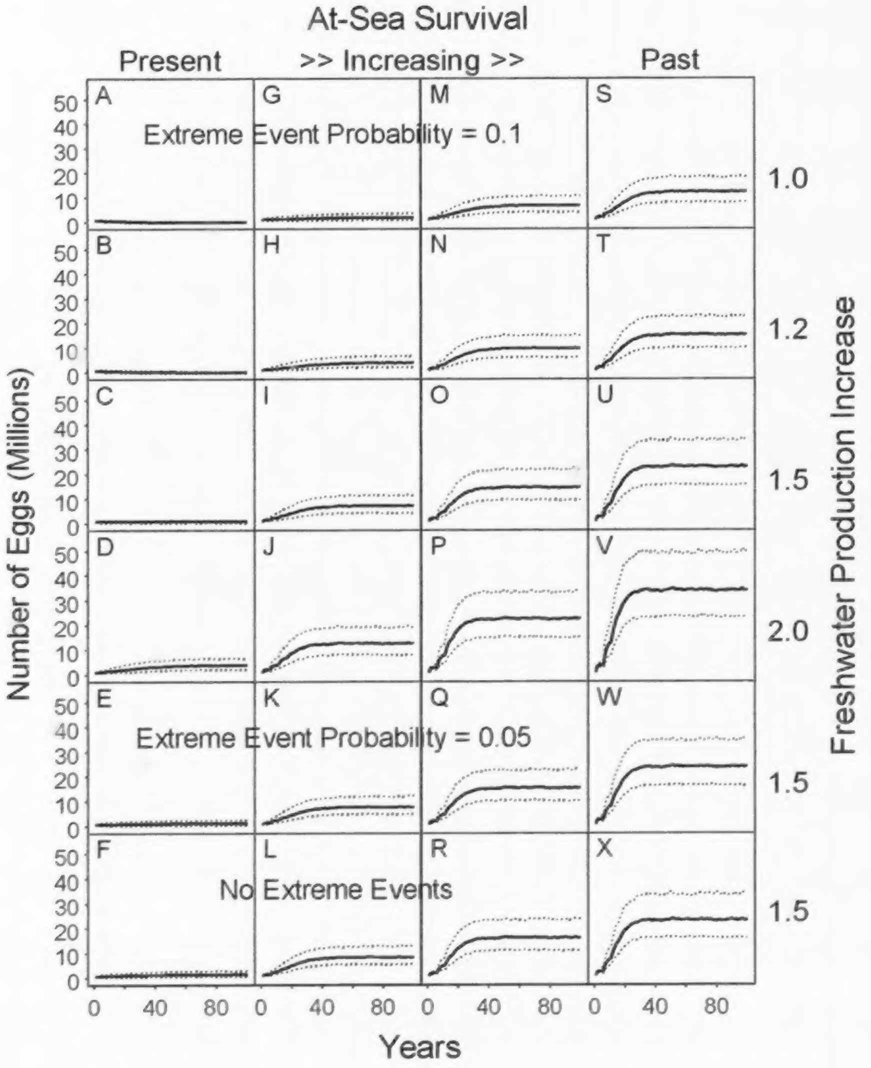

Figure 5.1. The effects of increasing at-sea survival and freshwater productivity on the simulated abundance of eggs for the LaHave River (above Morgans Falls) Atlantic salmon population. The graphs summarize 2000 simulations for each scenario. The median abundance (solid line), and the 10th and 90th percentiles (dashed lines) are shown. Panels on the right and the left are based on the 1980's and 2000's at-sea survival, respectively, and the middle panels show scenarios using survivals increased by 1/3 and 2/3's of the difference in these values. The return rates of 1SW and 2SW salmon and survival between repeat spawning events are increased. The 2000's freshwater production is used in all scenarios. The top four rows show the effect of increasing freshwater productivity by factors of 1 (no change), 1.2 (20% increase), 1.5 (50% increase) and 2.0 (100% increase). The bottom two rows show the effect of changing the frequency of event events to an average of 1 every 20 years (5th row) and to no extreme events (bottom row)

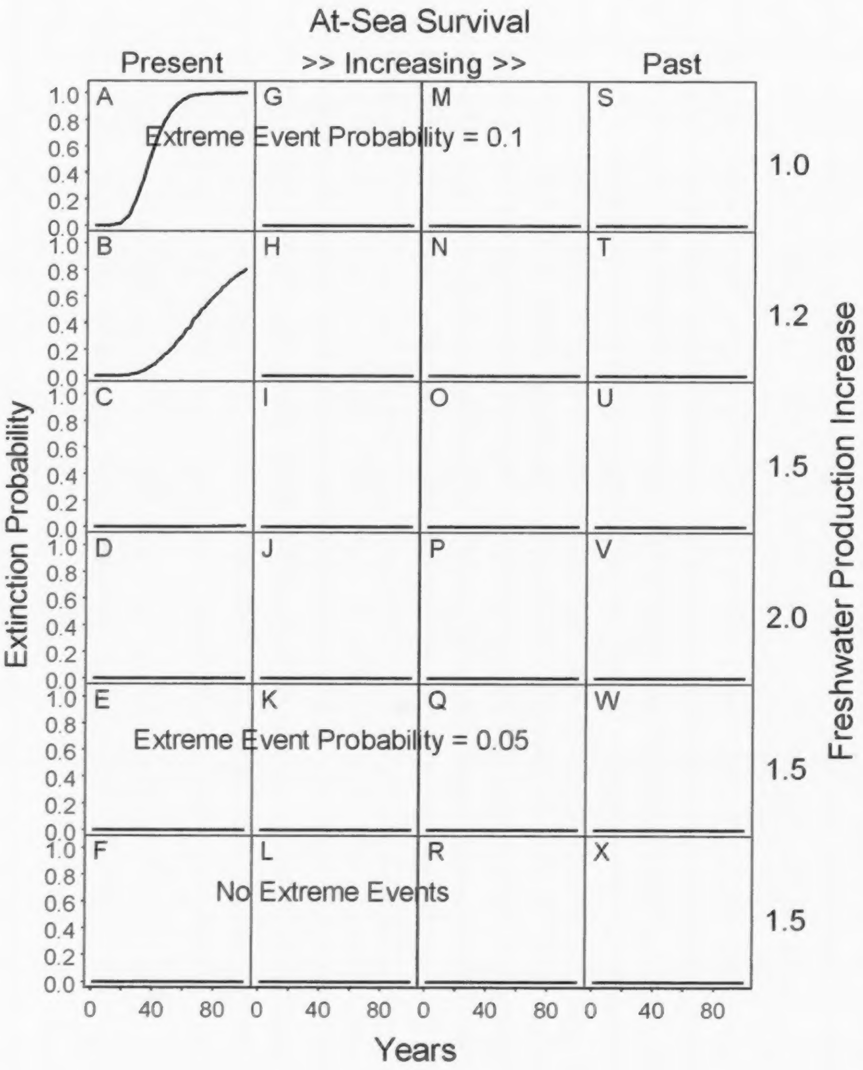

Figure 5.2. The effects of increasing at-sea survival and freshwater productivity on the probability of extinction for the LaHave River (above Morgans Falls) Atlantic salmon population. Panels are described in the caption for Figure 5.1.

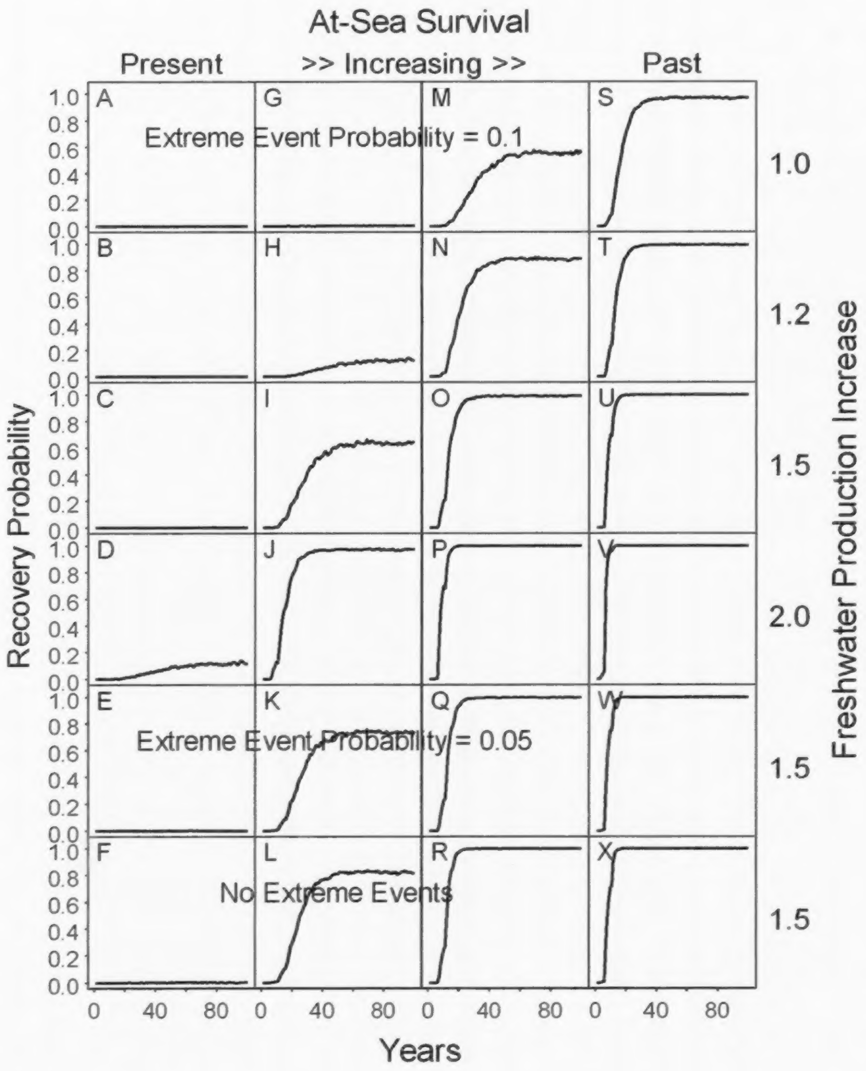

Figure 5.3. The effects of increasing at-sea survival and freshwater productivity on the probability of meeting the recovery target for the LaHave River (above Morgans Falls) Atlantic salmon population. Panels are described in the caption for Figure 5.1.

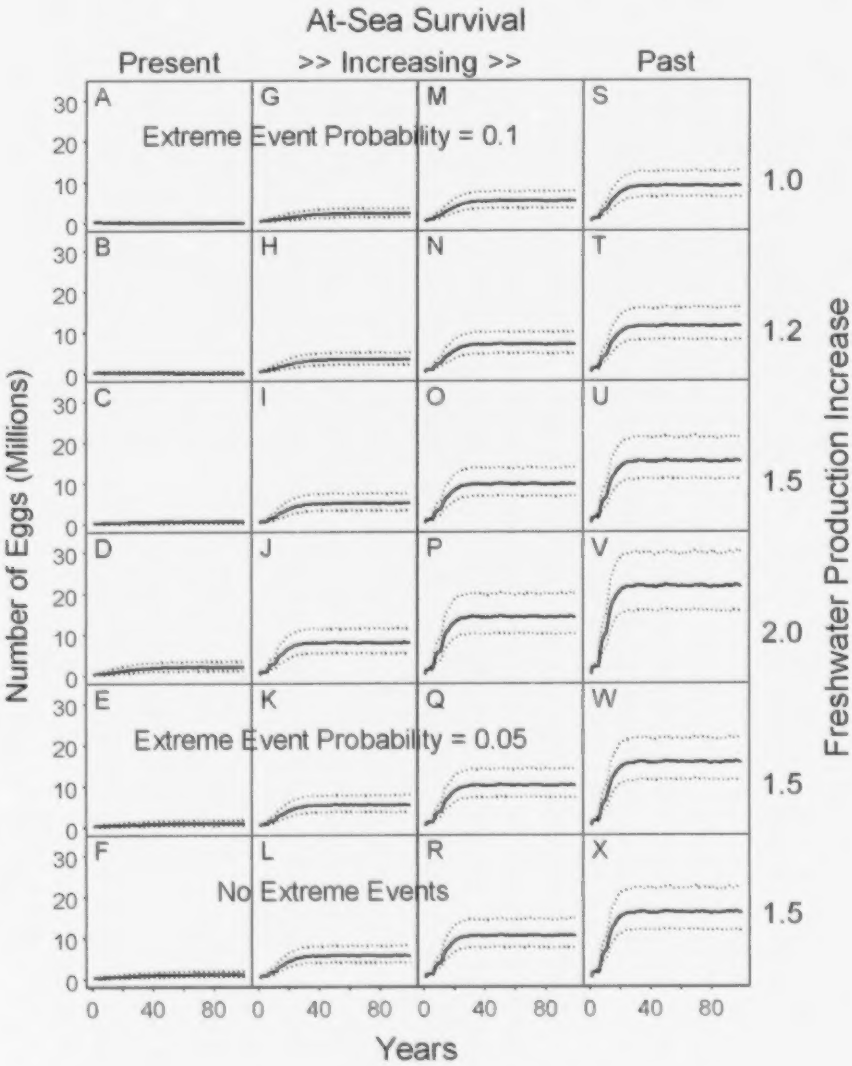

Figure 5.4. The effects of increasing at-sea survival and freshwater productivity on the simulated abundance of eggs for the St. Mary's River (West Branch) Atlantic salmon population. Panels are described in the caption for Figure 5.1.

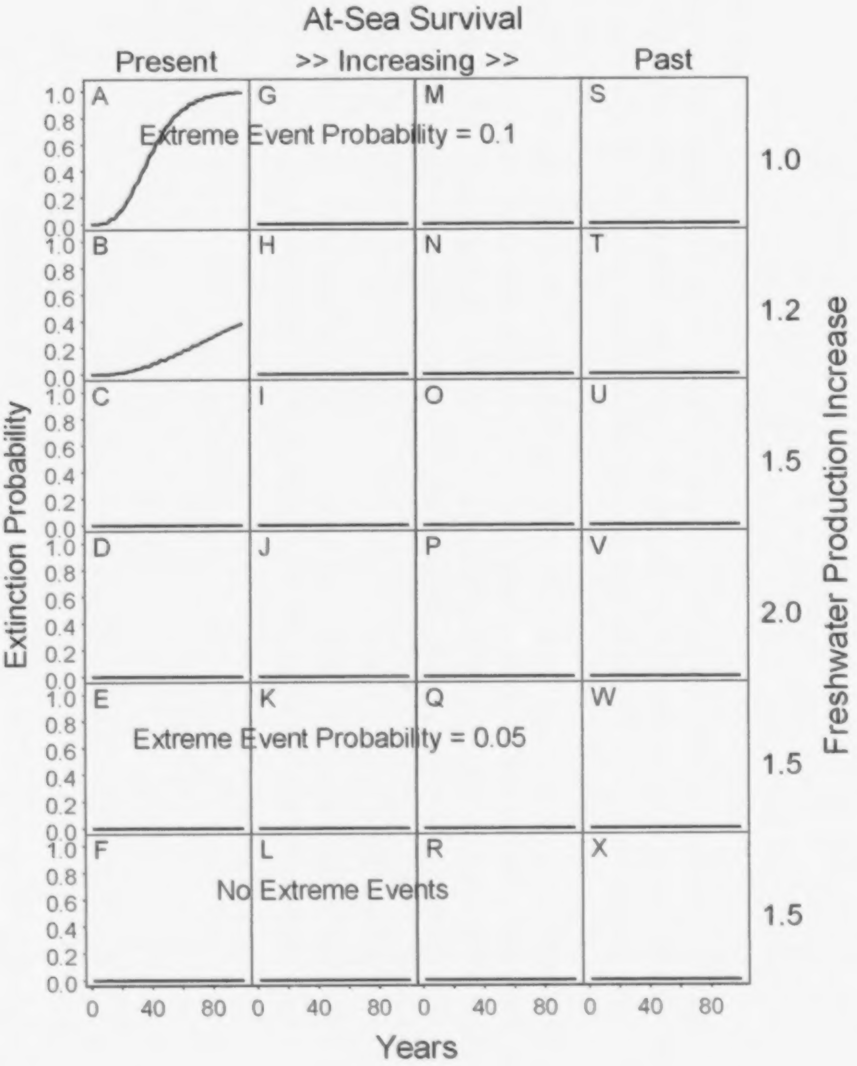

Figure 5.5. The effects of increasing at-sea survival and freshwater productivity on the probability of extinction for the St. Mary's River (West Branch) Atlantic salmon population. Panels are described in the caption for Figure 5.1.

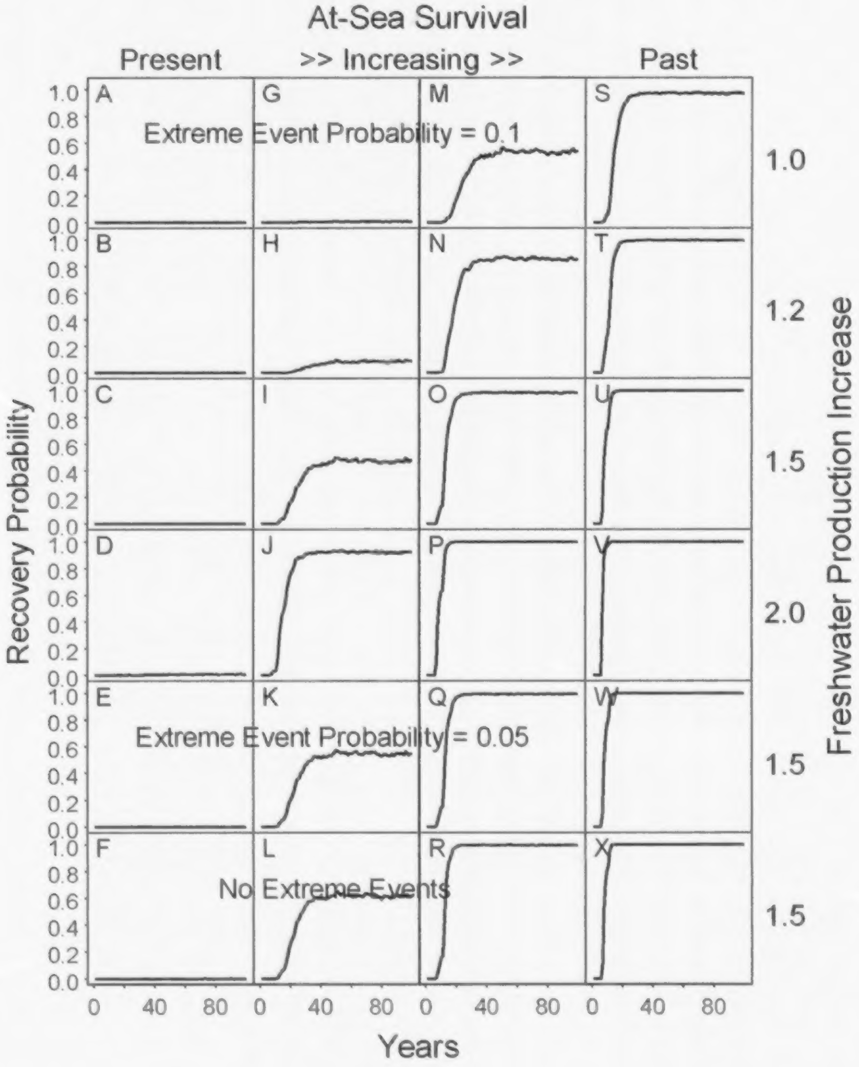

Figure 5.6. The effects of increasing at-sea survival and freshwater productivity on the probability of meeting the recovery target for the St. Mary's River (West Branch) Atlantic salmon population. Panels are described in the caption for Figure 5.1.

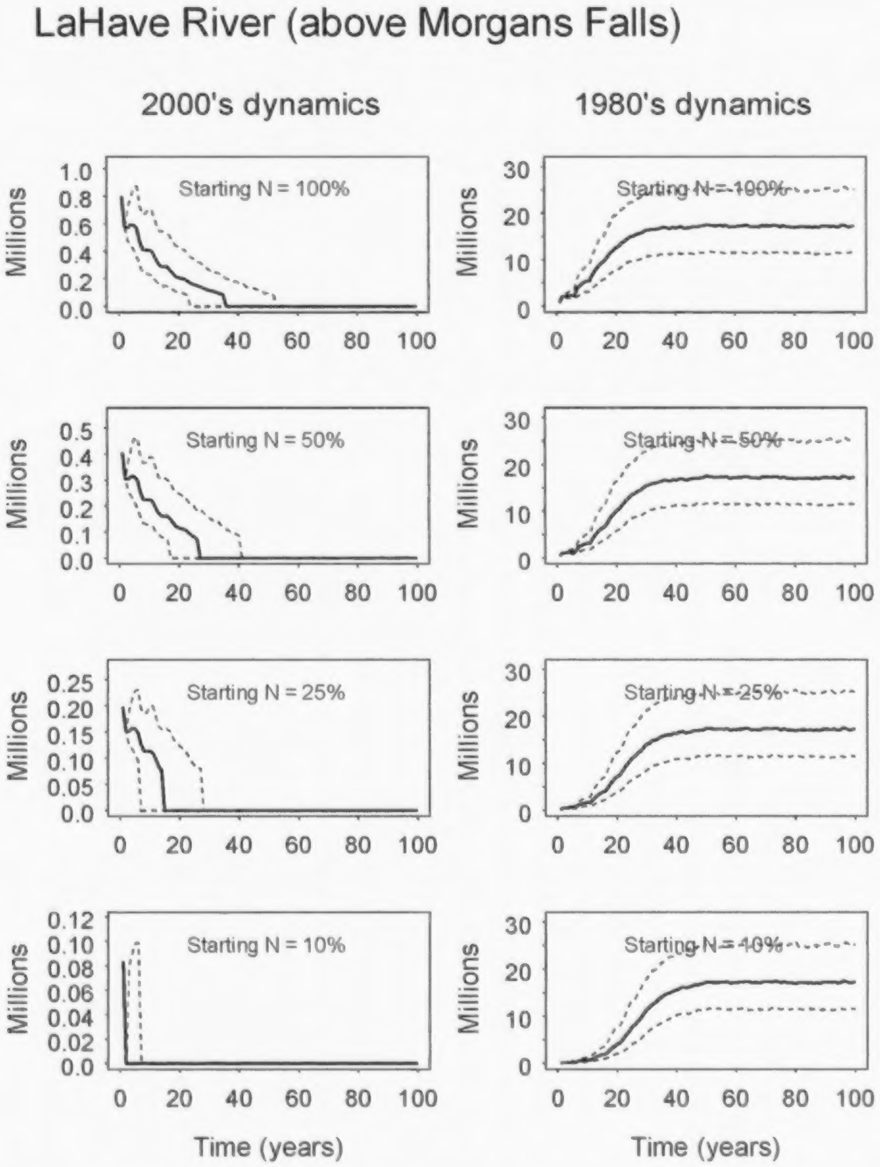

Figure 5.7. The effect of further reductions in population size on the abundance trajectories using base model for the LaHave River (above Morgans Falls) Atlantic salmon population. The graphs summarize 2000 simulations for each scenario. The median abundance (solid line), and the 10th and 90th percentiles (dashed lines) are shown. Panels on the right and left are based on the 1980's dynamics and 2000's dynamics, respectively. The top row shows the trajectories using the 2010 abundance estimate (300 small salmon and 53 large salmon) as the starting population size. The other rows show the effects of starting at 50%, 25% and 10% the 2010 abundance, respectively.

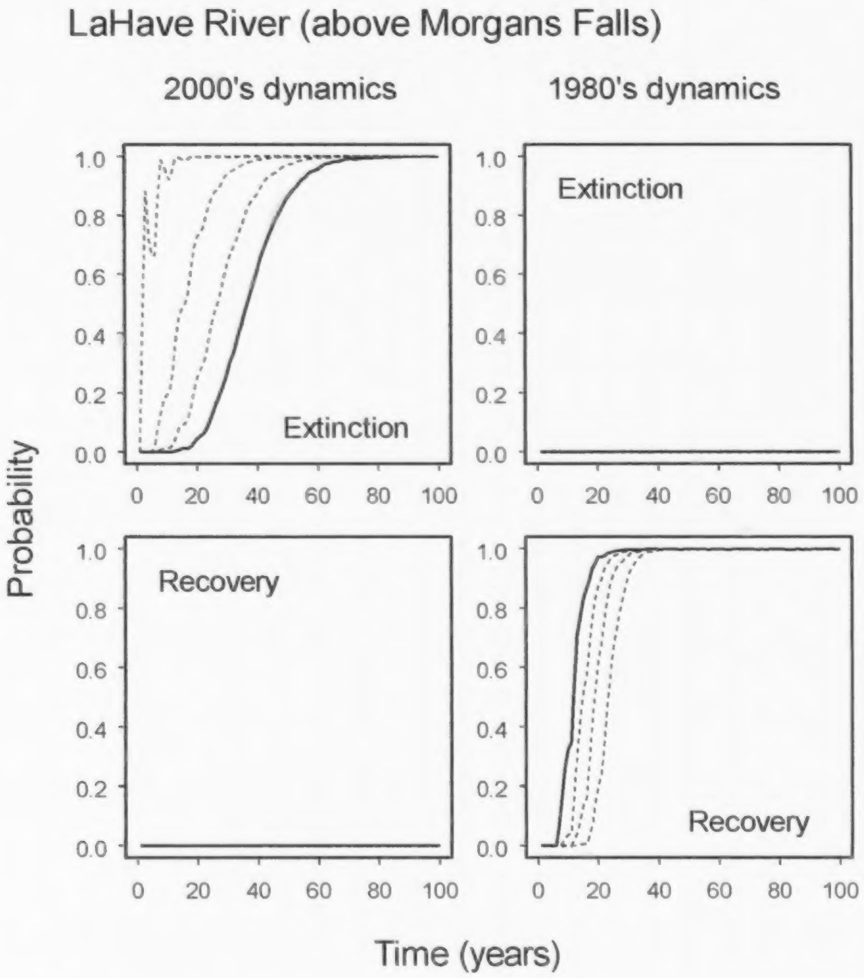

Figure 5.8. The probability of extinction (top row) and the probability of recovery (bottom row) as a function of time for the LaHave River (above Morgans Falls) Atlantic salmon population showing the effects of further reductions in population size. Scenarios are based on the 1980's dynamics (right panels) and on the 2000's dynamics (left panels). The solid lines show the probabilities when the starting population size is the estimated abundance in 2010 (300 small salmon and 53 large salmon). The other lines show the effects of starting at 50%, 25% and 10% the 2010 abundance (moving away from the solid line, respectively).

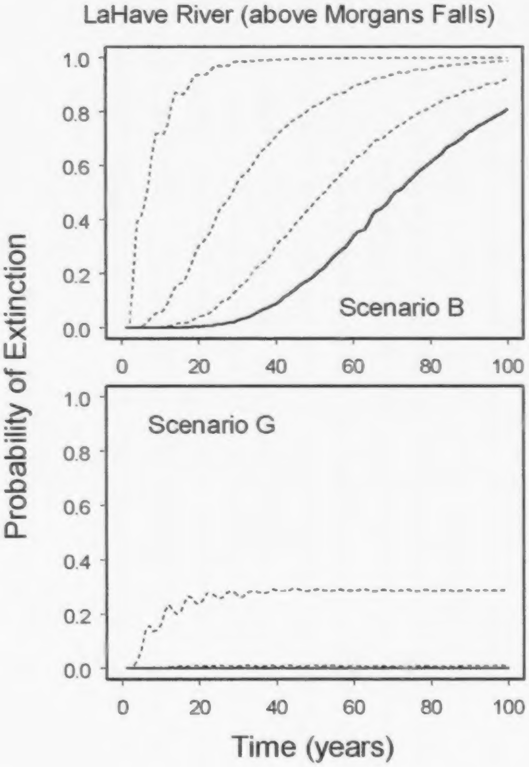

Figure 5.9. The probability of extinction as a function of time for two recovery scenarios for the LaHave River (above Morgans Falls) Atlantic salmon population showing the effects of further reductions in population size. Scenarios correspond with Figures 5.1 to 5.3. They are based on the 2000's dynamics with either an increase in freshwater production of 1.2 times (Scenario B) or an increase in at-sea survival of 1/3 the difference between the 1980's and 2000's values (Scenario G). The solid lines show the probability of extinction when the starting population size is the estimated abundance in 2010 (300 small salmon and 53 large salmon). The other lines show the effects of starting at 50%, 25% and 10% the 2010 abundance (moving away from the solid line, respectively).

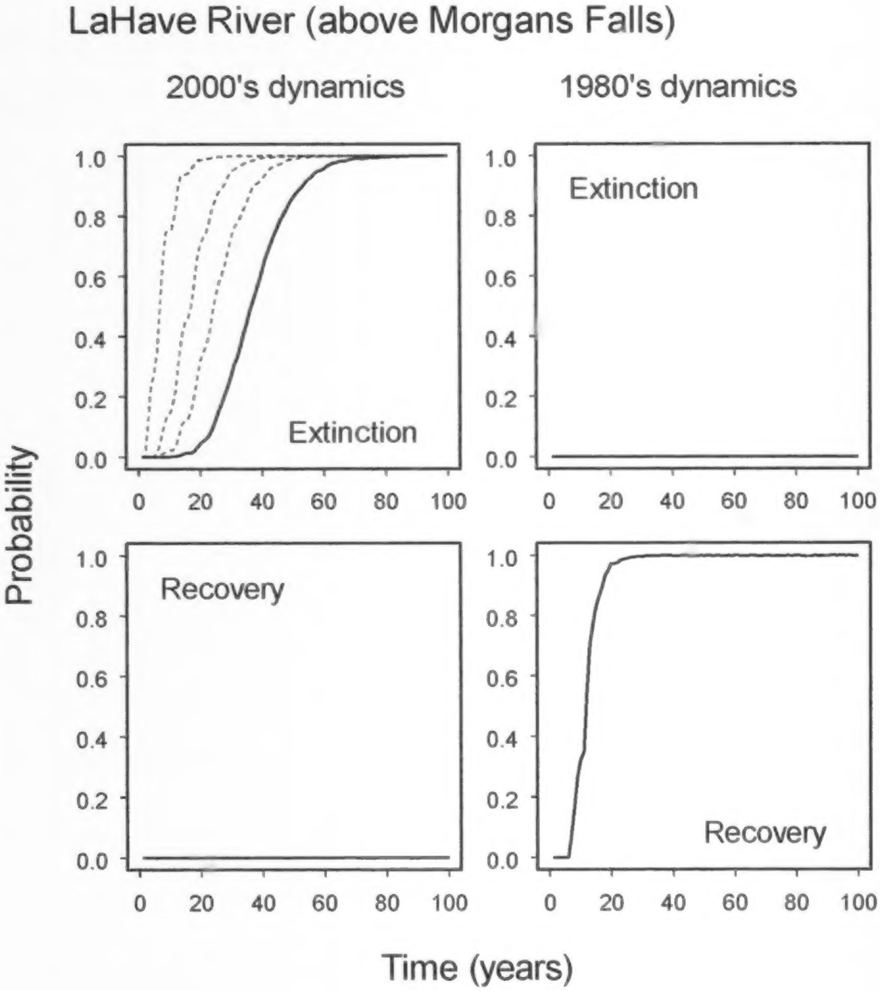

Figure 5.10. Sensitivity analyses showing the effect of the quasi-extinction threshold on the probability of extinction (top row) and the probability of recovery (bottom row) for the LaHave River (above Morgans Falls) Atlantic salmon population. Scenarios are based on the 1980's dynamics (right panels) and on the 2000's dynamics (left panels). The solid lines show the probabilities when the quasi-extinction threshold is set at 15 females. The other lines show the effects of setting the threshold at 30, 50 and 100 females (moving away from the solid line, respectively).

11. APPENDICES

APPENDIX 1. THE STATISTICAL, LIFE-HISTORY BASED POPULATION DYNAMICS MODEL USED FOR ESTIMATING LIFE HISTORY PARAMETER VALUES AND ANALYSING THE DYNAMICS OF SOUTHERN UPLAND ATLANTIC SALMON

The life history parameter estimates provided in Section 2.2, as well as the information on population dynamics in Section 2.5, were derived using a statistical, life-history-based population dynamics model developed by Gibson et al. (2008c, 2009b). The method follows the general theory developed by Fournier and Archibald (1982) and Deriso et al. (1985) for statistical catch-at-age models for stock assessment that allows auxiliary data to be incorporated for model fitting. Our approach is similar in that we are using multiple indices (auxiliary data) to derive estimates of the age- and stage-specific abundances and survival rates required to analyze the dynamics of these populations. The life history parameter estimates are then used to determine how recovery actions may be expected to change population size and viability.

As described in Section 2, the population dynamics model consists of two parts: a freshwater production model that provides estimates of the expected smolt production as a function of egg deposition, and a lifetime egg-per-smolt (EPS) model that provides estimates of the rate at which smolts produce eggs throughout their lives. These components are combined via an equilibrium analysis that provides estimates of the abundance at which the population would stabilize if the input parameters remained unchanged. This combined model is then used to evaluate how equilibrium population size has changed through time, as well as how the population would be expected to change in response to changes in carrying capacity, survival, or life stage transition probabilities, as described in Section 2.5.

The structure of the population dynamics model (freshwater production model component and the lifetime EPS model component) is described in Sections A1.1 and A1.2. The equilibrium model is described in Section A1.3. The statistical procedures used for parameter estimation and model fitting are described in Section A1.4.

A1.1 Freshwater Component of Life Cycle (Eggs to Smolts)

Model indices and parameter definitions for the freshwater component of the model are provided in Table A1.1 and the equations for characterizing dynamics in fresh water are provided in Table A1.2. A description of this model follows below.

The number of age-0 juveniles (or fry), at the time of the electrofishing surveys in the summer, is a function of egg deposition in the previous fall (calculated from total adult escapement in each year) multiplied by the egg to age-0 survival rate (equation 1, Table A1.2).

Density dependence was incorporated into the model via survival from age-0 to age-1 using a Beverton-Holt function, based on the results of Gibson (2006). Abundance of age-1 juveniles is a function of the maximum survival rate between age-0 and age-1, α , the asymptotic density of age-1 parr (maximum number per 100 m^2 habitat units - R_{asy}), an electrofishing catchability coefficient or scalar, h, and the probability that a fish emigrates as a smolt at age-1, j_1 (equation 2, Table A1.2). The product, $R_{asy}h$ is the carrying capacity of the river for age-1 parr. The model is formulated this way because the electrofishing data, used to estimate the number of parr, is reported as a density (number per 100 m^2), whereas our interest here is in the total number of parr in the river. The parameter h, which can be estimated within the model, is used to scale the parr density to the total abundance. Estimating the parameter, rather than using the measured number of habitat units, corrects for potential issues that would arise if the electrofishing sites fished each year were not representative of the entire river (Gibson et al. 2009b).

An implicit assumption made here is that the density of all age classes of parr can be scaled up to their respective abundances using a single value of h. This assumption is made because a set of age-specific catchabilities and mortalities would be completely confounded (covariance of 1) in the model without some sort of auxillary information about one parameter or the other (*sensu* Quinn and Deriso 1999). If the electrofishing sites are selected such that one age class is over- or under-represented in the sampling, the resulting age-specific mortality estimates would be biased, although the overall freshwater production curve would likely remain representative because the annual egg depositions and smolt abundance estimates do not have the same catchability issues.

The number of age-2 and older parr is determined by the number of parr in the cohort in the previous year, $P_{t-1,a-1}$, density-independent survival of parr, M_{Parr}, and the age-specific probability of smoltification, j_a (equation 3, Table A1.2). The number of smolt in each age and year class, $S_{t,a}$, is determined similarly (equation 4, Table A1.2). The maximum age at smoltification was assumed to be three for the St. Mary's River (West Branch), and four for the LaHave River (above Morgans Falls) populations, based on the observed ages of smolts during smolt monitoring in these rivers.

By combining the life stage-specific parameter estimates into a two parameter Beverton-Holt spawner recruitment function, it is possible to describe smolt production as a function of egg deposition. This is particularly convenient for the equilibrium population size calculations below to calculate overall freshwater productivity. Both parameters, the slope of the function at the origin (the maximum number of smolts produced per egg in the absence of density dependence) and the asymptotic recruitment level for smolts (the number of smolts that would be produced in a cohort if the egg deposition was infinite), can be calculated directly from the estimated parameters (equations 5 and 6, Table A.1.2).

A1.2 Lifetime Egg-Per-Smolt Model

The freshwater component of the life history model is used to characterize survival, productivity and stage-transition probabilities from the egg to the smolt stage, whereas the second part of the life history model characterizes the manner in which smolts produce eggs throughout their lives, abbreviated EPS (for eggs-per smolt). Model indices and parameter definitions for the EPS component of the model are provided in Table A1.3 and the equations characterizing these dynamics are provided in Table A1.4.

An important demographic parameter for evaluating the potential for population recovery is the rate at which smolts return to spawn for the first time, either as 1SW or 2SW salmon. One of the limitations of Atlantic salmon data is that the smolt abundance time series available for calculating return rates of adults are relatively short (1996-2010 on the LaHave and 2005-2009 on the St. Mary's) and the data are only available in recent years when abundance is low and decreasing. This makes it impossible to directly calculate return rates (indicative of marine survival) in earlier years, when abundance was higher, and to determine how population dynamics have changed such that populations are no longer viable. To address this issue, the estimated smolt abundance from the freshwater production model (described above) was used to extend the time series available for calculating return rates. Both the assessment on the St. Mary's River (West Branch) and the count at Morgans Falls provide estimates of the spawning escapement. Estimates of the return rates to escapement (i.e. the rate at which smolts return to spawn) for 1SW and 2SW salmon are calculated (equation 1, Table A.1.4) by dividing the number of salmon in each sea-age class by the estimated number of smolts emigrating either one or two years earlier (using smolt abundance estimates from the freshwater production model).

The sum of the mortalities associated with the recreational fishery (as a result of either retention or hook-and-release mortality) and the escapement for each sea-age group of adults provides an estimate of the returns of 1SW and 2SW fish to the river in a given year. Exploitation rates in fresh water are calculated from these values (equation 2, Table A.1.4). Return rates to the mouth of the river for each sea-age group are calculated from the group-specific exploitation rates and escapement estimates, as well as the estimated number of smolts emigrating either one year or two years earlier (equation 3, Table A.1.4).

The lifetime egg production per smolt (EPS) is the sum of the lifetime egg production of 1SW and 2SW salmon multiplied by their respective return rates (equation 4, Table A.1.4). The lifetime egg production for each sea-age category is a function of their size-specific fecundity, annual survival between spawning events, maximum number of spawnings and their probability of being either an alternate-year or consecutive-year repeat spawner (Equations 4.1 and 4.2, Table A.1.4). As written, the model does not allow salmon to switch between these categories.

A1.3 Equilibrium Calculations

As discussed in Section 2.5, equilibrium models are a useful way of evaluating the effects of human activities and life history changes on fish populations. The equilibrium egg deposition and number of smolts are denoted with asterisks to differentiate them from parameters in the freshwater life history model. Similarly, $\breve{\alpha}$ and $\breve{R}_{asy}$ represent the maximum rate of population growth and equilibrium population size for smolts in freshwater, respectively. The egg and smolt equilibrium values are calculated as follows:

Equilibrium egg deposition ($Eggs^*$) is:

$$Eggs^* = \frac{(\breve{\alpha}EPS - 1)\breve{R}_{asy}}{\breve{\alpha}},$$

and the equilibrium number of smolts (S^*) is found by substituting *Eggs** into the freshwater production model:

$$S^* = \frac{\breve{\alpha}Eggs^*}{1 + \frac{\breve{\alpha}Eggs^*}{\breve{R}_{asy}}}.$$

For the full derivation, see Gibson et al. (2009b).

A1.4 Parameter Estimation and Statistical Considerations

Maximum Likelihood

Parameter estimates for the freshwater production model were obtained by simultaneously fitting the model to the observed data using maximum likelihood by minimizing the value of an objective function, *OFV,* (Quinn and Deriso 1999). The *OFV* equals the sum of the negative log likelihoods for the juvenile electrofishing data ($\ell_{electro}$), the smolt age-frequency data (ℓ_{age}^{smolt}), the egg deposition data (ℓ_{egg}) and the smolt count data (ℓ_{smolt}). Lognormal error structures (Myers et al. 1995) were used for all likelihoods except the smolt age-frequency data, for which a multinomial likelihood (Quinn and Deriso 1999) was used. The objective function and the likelihood equations are provided in Table A1.5.

Estimating the variance for multiple lognormal likelihoods is problematic without other information about their variability. Gibson and Amiro (2003) had similar issues estimating the mean standard deviation of the likelihood estimates (σ) for all components of a similar model. Following their approach, we used the average values obtained by Myers et al. (1995) from spawner-recruit relationships of 15 populations of Atlantic salmon. For recruitment ages of 0, 1 and 2, σ equaled or averaged 0.33 (n = 1), 0.33 (n = 4) and 0.58 (n = 1), respectively, where n is the number of populations considered. Based on these results, we set σ equal to the median value, 0.33, for all age categories.

The parameters for the freshwater production model are listed in Table A1.1. The specific demographic parameters estimated are egg and parr mortality (M_{Egg} and M_{Parr}), the maximum survival rate from age-0 to age-1 for parr (α), the carrying capacity for age-1 parr (R_{asy}), and the smoltification probabilities at age (j_a). In addition, annual egg depositions for each year, and the electrofishing scalar were estimated in the model. Attempts were made to estimate parameter values for two time periods (by splitting the model and data into earlier and later time periods), but these attempts were only successful for the smoltification probabilities for the LaHave River.

The freshwater production model was programmed using AD Model Builder (Fournier 1996) which uses the C++ auto-differentiation library for rapid fitting of complex non-linear models, has Bayesian and profile likelihood capabilities, and is designed specifically for fitting these and similar types of models. We used the change in the Akaike Information Criterion (AIC) to help assess the trade-off between model fit to the data and the number of parameters in the candidate model (Hilborn and Mangel 1997). The model with the lowest AIC was generally selected as the preferred model. A similar approach was used to help select the best data input (for example, to choose whether to use standardized or un-standardized electrofishing data). To ensure that the model was not converging at a local (rather than a global) minimum, the model was run using several different sets of starting values. Standard errors for parameter estimates were calculated from the variance and correlation matrix generated by the Delta method (Efron and Tibshirani 1993). This is standard output from AD Model Builder (Fournier 1996).

Bayesian Analyses

Bayesian methods provide a powerful tool for assessing uncertainty in fisheries models (McAllister et al. 1994). Punt and Hilborn (1997) and McAllister and Kirkwood (1998) have reviewed their fisheries applications. The posterior probability distributions resulting from

Bayesian analyses show the uncertainty in model or policy parameters including both estimation uncertainty, as well as prior information about their values (Walters and Ludwig 1993). AD Model Builder (ADMB) uses a Markov Chain Monte Carlo (MCMC) algorithm (Carlin and Louis 1996) to approximate the posterior distribution for parameters of interest. MCMC is a stochastic simulation method used to evaluate complex integrals in order to derive posterior distributions. ADMB uses the Metropolis Hastings algorithm (Chib and Greenberg 1995) to generate the Markov chain, using a multivariate normal distribution based on the variance-covariance matrix for the model parameters as the proposal function. If the chain is long enough, the posteriors will be reasonably well approximated.

We assumed uniform bounded priors for all model parameters. Bounds were wide enough so as not to influence the fit. We used 4,000,000 iterations after a burn in of 400,000 iterations, and sampled every 4,000th iteration to derive the posterior distribution. This level of thinning was sufficient to ensure that autocorrelation in the chain was not problematic. Convergence of the Markov chain was inferred informally by comparing the similarity of the 10th and 90th percentiles of the posterior densities based on the first 2,000,000 iterations with those based on the second 2,000,000 iterations, and by comparison of the posterior densities from several chains (Gamerman 2000).

Table A1.1. Parameters and indices used in the freshwater production model. Indices are used as subscripts for years and age classes; estimated parameters are those that are estimated by the model using maximum likelihood; and derived parameters are those values calculated from the estimated parameters.

Model parameter	Description	Type
t	Time in years	index
a	Juvenile age	index
Egg_t	Egg deposition in year t	estimated
M_{Egg}	Egg-to-fry mortality rate	estimated
$P_{t,0}$	Abundance of fry (age-0) in year t	derived
$D_{t,0}$	Density of fry (age-0) in year t	derived
α	Maximum survival from age-0 to age-1 (slope at the origin of the Beverton-Holt model)	estimated
R_{asy}	Asymptotic age-1 density (N/100 m^2)	estimated
h	Electrofishing scalar (habitat area in m^2)	constant or estimated
$P_{t,a}$	Abundance of parr of age a in year t	derived
$D_{t,a}$	Density of parr of age a in year t	derived
M_{Parr}	Parr mortality rate (age-1 and older)	estimated
j_a	Probability of smolting at age a	estimated
$S_{t,a}$	Abundance of smolt of age a in year t	derived
σ	Standard deviation for the likelihood functions	constant (0.33)
$\tilde{\alpha}$	Maximum number of smolts produced per egg (slope at the origin of the Beverton-Holt model)	derived
$\tilde{R}_{asy}$	Carrying capacity for smolts	derived

Table A1.2. Model equations for the freshwater production component of the population dynamics model.

	Description	Equation
1	Abundance of fry (age-0) in year *t*	$P_{t,0} = Egg_{t-1}(1 - M_{Egg})$
2	Abundance of age-1 parr in year *t* (incorporating density dependence)	$P_{t,1} = \dfrac{\alpha P_{t-1,0}}{1 + \dfrac{\alpha P_{t-1,0}}{R_{asy}h}}(1 - j_1)$
3	Abundance of age-2 and older parr in year *t*	$P_{t,a} = P_{t-1,a-1}(1 - M_{Parr})(1 - j_a)$
4	Smolt abundance in year *t* of age *a*	$S_{t,a} = P_{t-1,a-1}(1 - M_{Parr})(j_a) \qquad a = 1,2,3,4$
5	Maximum survival from egg to smolt	$\bar{\alpha} = \alpha(1 - M_{Egg})\left[j_1 + \sum_{a=2}^{4}\left[j_a\left(\prod_{k=1}^{k=a-1}(1 - j_k)\right)(1 - M_{Parr})^{a-1}\right]\right]$
6	Carrying capacity of the river for smolts	$\bar{R}_{asy} = R_{asy}h\left[j_1 + \sum_{a=2}^{4}\left[j_a\left(\prod_{k=1}^{k=a-1}(1 - j_k)\right)(1 - M_{Parr})^{a-1}\right]\right]$

Table A1.3. Parameters and indices used in the lifetime EPS model. Indices are used as subscripts for years and age classes, derived parameters are those values calculated from the estimated parameters, and data are values such as counts that are used as model inputs for calculations (assumed known without error).

Model parameter	Description	Type
c	Number of years as an immature salmon at sea	index
ps	maximum number of spawning events per individual	index
$Esc_{t,c}$	Spawning escapement of salmon of sea-age c in year t	data
$C_{t,c}$	Number of salmon of sea-age c removed by the recreational fishery in year t	data
$u_{t,c}$	Exploitation rate of salmon of sea-age c in year t	derived
M_{Mat}	Mortality between spawning events	data
p_{alt}	Probability of repeat spawning in alternate years	data
f_1	Fecundity of 1SW females (# of eggs)	data
f_2	Fecundity of MSW females (# of eggs)	data
RR_c^{river}	Return rates of salmon of sea-age c to the mouth of the river	derived
$RR_c^{escapement}$	Return rates of salmon of sea-age c to spawning escapement	derived
EPS	Lifetime egg production per smolt	derived

Table A1.4. Model equations for the lifetime EPS component of the population dynamics model. Parameter definitions are provided in Tables A1.3 and A1.1 (freshwater component of the model).

	Description	Equation
1	Return rates to the assessment facility/location for salmon of sea-age *c* in smolt year class *t*	$RR_{t,c}^{escapement} = \dfrac{Esc_{t+c,c}}{\sum_{a=2}^{4} S_{t,a}}; \quad c = 1,2$
2	Exploitation rates for salmon of sea-age *c* in smolt year class *t*	$u_{t,c} = \dfrac{C_{t+c,c}}{C_{t+c,c} + Esc_{t+c,c}}; \; c = 1,2$
3	Return rates to the mouth of the river for salmon of sea-age *c* in smolt year class *t*	$RR_{t,c}^{river} = \dfrac{Esc_{t+c,c} / (1-u_{t,c})}{\sum_{a=2}^{4} S_{t,a}}; \; c = 1,2$
4	Lifetime egg deposition per smolt in smolt year class *t*	$EPS_t = \sum_{c=1}^{2} RR_{t+c,c}^{escapement} Egg_c$
		where:
4.1	Lifetime egg deposition for a 1SW salmon	$Egg_1 = f_1 + (1-p_{alt}) \sum_{k=1}^{ps} (1-M_{mat})^k f_2 + p_{alt} \sum_{k=1}^{ps} (1-M_{mat})^{2k} f_2$
4.2	Lifetime egg deposition for a 2SW salmon	$Egg_2 = f_2 + (1-p_{alt}) \sum_{k=1}^{ps} (1-M_{mat})^k f_2 + p_{alt} \sum_{k=1}^{ps} (1-M_{mat})^{2k} f_2$

Table A1.5. Likelihood functions and the objective function used for fitting the freshwater component of the population dynamics model.

	Description	Equation
1	Egg likelihood	$\ell_{egg} = -n \ln \sigma_{egg} \sqrt{2\pi} - \sum_t Egg_t^{obs} - \dfrac{1}{2\sigma_{egg}^2} \sum_t (\ln Egg_t^{obs} - \ln Egg_t)^2$
2	Electrofishing likelihood	$\ell_{electrofiking} = \sum_a \left(-n \ln \sigma_{elect} \sqrt{2\pi} - \sum_t D_{t,a}^{obs} - \dfrac{1}{2\sigma_{elect}^2} \sum_t (\ln D_{t,a}^{obs} - \ln(P_{t,a} / h))^2 \right)$
3	Smolt likelihood	$\ell_{smolt} = -n \ln \sigma_{smolt} \sqrt{2\pi} - \sum_t S_t^{obs} - \dfrac{1}{2\sigma_{smolt}^2} \sum_t (\ln S_t^{obs} - \ln S_t)^2$
4	Smolt age-frequency likelihood	$\ell_{age}^{smolt} = \sum_t \log \left(\dfrac{n_{smolt t}!}{(x_{smolt t,1}!)(x_{smolt t,2}!) \ldots (x_{smolt t,r}!)} p_{smolt t,1}^{x_{smolt t,1}} \ldots p_{smolt t,r}^{x_{smolt t,r}} \right)$
5	O.F.V. value	$O.F.V. = -(\ell_{egg} + \ell_{smolt} + \ell_{electrofiking} + \ell_{age}^{smolt})$

APPENDIX 2. LIFE HISTORY PARAMETER ESTIMATION FOR THE LAHAVE RIVER (ABOVE MORGANS FALLS) ATLANTIC SALMON POPULATION

The life history parameter estimates provided in Section 2.2, as well as the information on population dynamics in Section 2.5, were derived using the statistical, life-history-based population dynamics model described in Appendix 1. The application of the model to the LaHave River (above Morgans Falls) Atlantic salmon population, including descriptions of the data series used in the analyses and their derivations, alternate model runs, and the reasoning and biological justification for selecting the preferred model, is described in this appendix.

A2.1 Data

Adult Abundance and Biological Characteristics

Adult abundance for the LaHave River (above Morgans Falls) population is determined by enumerating the number of adults ascending a vertical slot fishway at Morgans Falls (Gibson et al. 2011). This fishway, constructed in 1969, provides access to 51% of the habitat in the LaHave River watershed (Amiro et al. 1996). These counts are believed to enumerate the total returns to the area above Morgans Falls because the fish ladder provides access to habitat upstream of a nearly impassable barrier, and the counting facilities are operated for the entire duration of the spawning migration (mid-spring to late fall). Salmon are marked using a tail punch prior to release above the ladder to ensure they are not double counted if they move downstream and then ascend the ladder for a second time.

After ascending the fishway, salmon are captured in a trap where they are sampled in order to collect data on the biological characteristics of the spawning run. Fork length and weight are measured and the sex and origin (hatchery or wild – determined by whether or not the fish has an adipose fin clip) of each fish is determined. Scale samples are collected from a percentage of the run in order to determine the age structure of the spawning population with an emphasis on aging large salmon (Hubley 2010) because small salmon are virtually all sea-age one. The proportion of the run sampled has increased over time as abundance has decreased (Table A2.1).

In this analysis, the adult counts and biological characteristics are used for three purposes. First, these data are used to estimate the annual egg depositions (described below). Second, the data are used to determine the number of 1SW and 2SW first-time spawning salmon returning to Morgans Falls based on the proportions of the total run that are in each of these groups. These estimates are then used to calculate the smolt-to-adult return rates to Morgans Falls as described in Appendix 1 (equations in Table A1.4). Third, the data are used to characterize the repeat spawning dynamics of salmon in this population, as summarized in Section 2.4 and described in detail in Hubley and Gibson (2011).

Throughout the analysis, with the exception of the egg deposition (which includes the contribution from hatchery-origin spawners), the emphasis is on dynamics of wild Atlantic salmon. As such, the numbers of virgin 1SW and 2SW salmon returning to Morgans Falls, the proportions of virgin 2SW in the large component of the population, and the proportions of large and small salmon provided in Table A2.2 are that of wild origin.

Recreational Fishery Statistics

Catch and effort data from the annual recreational Atlantic salmon fishery (Table A2.3) have been collected using a license-stub return program since 1983 (Gibson et al. 2011). After the close of the fishing season, anglers return license stubs on which they have recorded the dates and rivers where they fished for salmon, as well as their catch (if any). Large salmon (fork length of 63 cm or larger) and small salmon (less than 63 cm fork length) are recorded separately. The catch is corrected for non-reporting using a regression developed from the change in the reported catch resulting from sending multiple reminder letters to increase the number of returned license stubs. Prior to 1983, annual recreational harvests are those estimated by Fishery Officers and were collated by Swetnam and O'Neil (1984) and O'Neil and Swetnam (1984). Effort was estimated in rod days where any portion of a day fished by one angler was recorded as one rod day (effort is reported here but not used in the model).

The recreational fishery statistics are used in this analysis to estimate the smolt-to-adult return rates to the mouth of the river (i.e. before any removals by the recreational fishery) as described in Appendix 1 (equations in Table A1.4), by adding the number of virgin 1SW and 2SW salmon estimated to have been removed by the fishery to the numbers counted at Morgans Falls. The numbers of virgin 1SW and 2SW wild salmon removed by the fishery are calculated from the number of large and small salmon reported in the recreational fishery statistics using the biological characteristics of the population sampled at Morgans Falls, including an adjustment for the proportion of salmon that are of hatchery origin. A hook-and-release mortality estimate of 4% was applied in the analysis, consistent with recent assessments (e.g. DFO 2011). In addition, the recreational fishery statistics are reported for the entire LaHave River and include salmon destined for areas other than above Morgans Falls. In the model, it is assumed that 51% of the catch and harvests are of fish destined for above Morgans Falls. This value is the proportion of the total habitat in the watershed that is located above Morgans Falls. It is very similar to the estimated proportion of the LaHave River population that spawns above Morgans Falls (49%), a value determined via a tagging study done in 1983 (Amiro et al. 1996, Amiro and Jefferson 1998). In this study, adult salmon and grilse were tagged at Pleasantville on the west side of the LaHave River estuary. The estuarial trap operated from May 21 to August 7, 1983 (Amiro and Jefferson 1998). A total of 204 tags (199 Carlin tags and 5 floy tags) were applied. Amiro et al. (1996) used the data to estimate the total abundance of salmon in the LaHave River in 1983, and compared this value to the count at Morgans Falls to this estimate to obtain this proportion. To date, this is the only experimental basis for determining the proportion of the LaHave River salmon population that spawns above Morgans Falls.

Egg Deposition Time Series

The annual egg depositions in the LaHave River above Morgans Falls were calculated using the count of salmon at the Morgans Falls fish ladder, their biological characteristics, and a population-specific length-fecundity relationship for female salmon. The egg deposition time series used in the model is provided in Table A2.2.

A key decision in calculating this series was whether the series should include both hatchery-origin and wild salmon, or whether only wild salmon should be used in its derivation. Although hatchery-origin salmon have been found to have lower spawning success relative to wild individuals (McGinnity et al. 2004, Weir et al. 2004, Jonsson and Jonsson 2006, Chilcote et al. 2011), they are still expected to contribute to subsequent juvenile production. At present, there is no way to identify whether juvenile salmon in this population are the progeny of cultured or wild salmon spawning in the wild. Therefore, the decision was made to include cultured salmon when calculating the number of eggs deposited each year.

Smolt Abundance and Biological Characteristics

The annual smolt migration for the LaHave River (above Morgan Falls) salmon population was monitored from 1996 to 2010. Monitoring occurs at an assessment facility installed downstream of the fish louver by-pass screens in the intake canal to the Morgan Falls Power Company's low-head 1.5 kW hydro generating plant (Amiro and Jefferson 1998). The assessment facility is operated by manipulating a gate system in order that smolts can be collected in a shallow assessment tank and examined before being re-routed to the downstream by-pass (Amiro and Jefferson 1998). Abundance estimates are obtained via a mark-recapture experiment in which a portion of the smolts are tagged, transported upstream about 2 km into New Germany Lake and recaptured as they pass through the assessment facility a second time. As described in the Bowlby et al. (2013a), single Peterson mark-recapture estimates were used for all years except 2010, when a stratified estimate was used.

Biological characteristics are collected from a sample of smolts captured during the assessment. The fork length and weight of sampled individuals is recorded and a scale sample is collected to determine the smolt's age. Abundance estimates and the number of sampled smolts in each age category from 1996 to 2010 are provided in Table A2.4 (the numbers in category are provided, rather than the proportions because this is how the data are input into the model). The time period over which smolt data has been collected is relatively short in comparison with the adult times series. A second way to determine the age structure of smolts (one that is not dependent on sampling them directly) is to use the river-ages (i.e. time spent in fresh water) from the scale samples of wild returning adults. This assumes that post-smolt survival at sea is not dependent on age. The time series of river-ages, also provided in Table A2.4, has the advantage that it is much longer and therefore could be informative about changes in freshwater productivity that would not be evident if the shorter time series based on smolt monitoring was used.

Abundance of Fry and Parr

The relative abundance of age-0 (fry), age-1 and age-2+ (collectively known as parr) juvenile salmon in the LaHave River is determined by electrofishing. Note that here, the notation 2+ is used to denote a plus group consisting of all parr age-2 and older, consistent with the way this notation is used for other species (Quinn and Deriso 1999). In these analyses, only electrofishing data collected above Morgans Falls are used. The annual electrofishing surveys roughly follow a random-stratified design for site selection (Amiro et al. 1989, Amiro 1993), a method that is thought to give a more unbiased estimator of mean annual density because sampling takes place over the range of available habitat types (Gibson et al. 2008a). Sites were originally selected randomly in proportion to the stratum areas (distance from mouth and stream gradient), after which the survey became a fixed station survey using the randomly selected sites. However, sites did change somewhat over time because some sites became inaccessible and the number of sites varied from year to year due to varying weather conditions, resource availability and priorities.

Four key decisions had to be made about the juvenile density data in the model: how to best estimate site-specific juvenile abundance from the data; how to best determine abundance-at-age; whether data from all sites should be included in the analysis; and whether the data should be standardized to correct for changes in the location of sites from year to year.

The methods used during the electrofishing surveys on the LaHave River have changed through time. In the early part of the time series, multiple pass depletion methods were used, which shifted to primarily mark-recapture methods in the early 1990's. During more recent years, abundance has been low enough at some sites that neither method would be applicable, so single pass electrofishing occurred. For single pass sites, a capture efficiency from depletion methods or mark-recapture sites (fished either in the same year or in the previous year) was applied in recent assessments to obtain a density estimate (e.g. DFO 2011). However, both mark-recapture and depletion methods have potential biases. Rather than using the catchability estimates from a small group of individual sites, the number of salmon captured per unit area on the first pass at each site was used as a standard index of abundance, and the average catchability over all sites was used to covert these values to densities. Separate catchabilities were derived for fry and parr.

Two methods of determining the proportions-at-age for the parr were evaluated: the highly subjective method of examining the length-frequency distributions by eye and assigning ages based on a criterion length (chosen by eye); and the statistically robust method of fitting an age-length key to the available data (Quinn and Deriso 1999). Because there are only two age groups of parr (age-1 and age-2+), the age-length key can be solved using logistic regression. After fitting the regression model to the age-length data, the probability that a salmon of given length is either age-1 or age-2+ can be calculated and these probabilities are then summed to obtain estimates of the proportions-at-age for the population in each year.

Although there are many scale samples available for the juvenile salmon population above Morgans Falls, most the data derived from these samples is not currently in a form which is amenable to developing an age-length key. However, there were eight years in which length at age for individual parr could be determined from scale samples in the database under development for storing this information. The lengths and ages of individual parr indicate an overlap in length-at-age (Figure A2.1). A visual comparison of the logistic regression lines indicates that the fork length at which 50% of the parr would be classified as age-1 or as age-2 has varied from about 140 mm to greater than 150 mm. This variation could result for several reasons, including density dependent growth (e.g. Gibson et al. 2008a) or differences in the timing of sampling from year to year. When developing the age-length keys for all years, the year-specific regressions for the years was used when data was available in the database (i.e. the years listed in Figure A2.1) and the average relationship was used for all other years. This method is not entirely satisfactory given the amount of year-to-year variability in the regressions. As an alternative to using the age-length key, the length frequency distributions were examined and estimated the proportions-at-age by eye. This was done on an individual site basis to address variation in size-at-age among sites (Strothotte et al. 2005). This method introduces an element of subjectivity into the analysis, and does not address the issue of the overlap in size-at-age shown in Figure A2.1, but does address the issue of year-to-year variability because considerably more length information is currently available in the database.

Specific sites have been included in the annual electrofishing surveys on the LaHave River for various purposes, although an overall goal of the survey has always been to derive a consistent abundance index. In some years in the early 1980's (and again in 1995), several single pass sites (primarily in the headwaters) were added to the survey to determine how far upstream salmon had moved when colonizing the river (Eric Jefferson, personal communication). In order to evaluate the effect of including or not including these sites when deriving the relative abundance time series, two series were derived: one using all the data and the other using only sites that had been fished in three or more years.

The number of sites electrofished has varied from year-to-year, ranging between 2 and 23 (out of a total of 35 sites). Such variation in sample locations can bias the resulting density estimates if the proportions of high and low density sites change annually or systematically over time, and this in turn can bias survival estimates (Gibson et al. 2008c). Therefore, a generalized linear model (GLM) was used to reduce overall variation in the time series of estimated age-class densities, and to investigate how such variation in sample locations influences the predictive capacity of juvenile data. Following the approach in Gibson et al. (2008c), mean density of a given age class was estimated for each year using 'site' and 'year' as factors in the GLM, assuming a Poisson error distribution. Gibson et al. (2008c) found that the standardized data provided better estimates of survival and a significantly better model fit when modelling the dynamics of Tobique River Atlantic salmon using methods similar to those presented herein. For the three juvenile age classes in the LaHave River above Morgans Falls, we derived abundance indices using both standardized and un-standardized data.

There were eight candidate variations of the juvenile data series derived using the methods above. Although all variations were tested in the model, three are presented in this manuscript: (1) juvenile time series that had been standardized to correct for site variation among years using a GLM, with the proportions at age for parr determined from an age-length key and using only sites that had been fished more than two times; (2) juvenile time series that had been standardized with a GLM, and using sites only that have been fished more than two times, but where the proportions at age for parr were determined by length frequencies; and (3) juvenile time series that were not standardized with a GLM, used data from all sites, and estimated the proportions at age for parr from visual examination of length frequencies. These three sets of age-0, age-1 and age-2+ abundance indices used for model runs are provided in Table A2.5.

A2.2 Model Formulations

The model was set up using data from 1975 to 2010. The estimated demographic parameters for the freshwater production model are listed in Table A2.6. These include the annual mortality rates of eggs and parr (M_{Egg} and M_{Parr}), the maximum survival rate from age-0 to age-1 for parr (α), the carrying capacity of freshwater habitat for age-1 parr (R_{asy}), and the smoltification probabilities at age ($j_2\ and\ j_3$) for both an early time period and later time period using a step function. This is similar to splitting the data into two time periods, but is accomplished in a single integrated analysis. The break year for the step function (1985) was chosen by profiling over all possible break years and choosing the year with the lowest OFV (see Appendix 1 for the description of the objective function value). We attempted to use step functions for other freshwater model parameters (to test for changes in other life history parameters), but could not obtain reasonable model fits. In particular, we had difficulty estimating α when abundance was higher in the earlier time period, and R_{asy} in the later time period when abundance was lower. Although the timing and magnitude of changes in life history parameters are almost certainly more variable than shown here, the step function enabled us to more accurately model the changes in the smolt age distribution over time.

In addition to the demographic parameters, annual egg depositions for each year (36 parameters), as well as the electrofishing scalar h, were estimated with the model. In total, 45 parameters were estimated. Consistent with Gibson et al. (2008c), we found that estimating the annual egg depositions, rather than using the data as constants in the model, improved the model fit. This approach allows for errors in the annual egg deposition data that could arise from annual variability in fecundity, fallback at Morgans Falls, or some other factors.

The preferred, or base model run, consisted of using the standardized electrofishing time series derived using sites that had been fished more than two times and using the age composition derived from the length-frequency data (i.e. columns labelled: GLM / <2yr / l.f. in Table A2.5);

as well as the adult river ages to estimate the smolt numbers-at-age. Examples of other model runs are shown in Table A2.6, including:

- Model 2: using the standardized electrofishing time series derived using sites that had been fished more than two times and using the parr age composition derived from the age-length key (columns labelled: GLM / <2yr / reg. in Table A2.5); as well as the adult river ages used to estimate the smolt numbers-at-age.
- Model 3: using the un-standardized electrofishing time series derived using all sites and using the age composition derived from the length-frequency data (columns labelled: no GLM / all / l.f. in Table A2.5); as well as the adult river-ages used to estimate the smolt numbers-at-age.
- Model 4: using the standardized electrofishing time series derived using sites that had been fished more than two times and using the age composition derived from the length-frequency data (columns labelled: GLM / <2yr / l.f. in Table A2.5); as well as the smolt ages used to estimate the smolt numbers-at-age.
- Model 5: using the un-standardized electrofishing time series derived using all sites and using the age composition derived from the length-frequency data (columns labelled: no GLM / all / l.f. in Table A2.5); as well as the smolt ages used to estimate the smolt numbers-at-age.

The relative contribution of each likelihood to the objective function can be controlled using a set of weighting values. These values may be selected to keep any one part of the objective function from dominating the fit, or alternatively, to reflect perceptions of data accuracy (Merritt and Quinn 2000). Here, all weights were set equal to one, an approach that has the advantage that the OFV can be interpreted as the likelihood. Several other data combinations and data (likelihood) weighting combinations were evaluated as well. Although the parameter estimates varied slightly in each case, none of these other model runs altered the conclusion that the dynamics exhibited in the base model are a reasonable approximation of the dynamics of the LaHave River (above Morgans Falls) population at this time.

A2.3 Results

Parameter estimates are provided in Table A2.6 and model fits and diagnostic plots for the base model run are shown in Figures A2.2 to A2.10. Overall the model fits to the data appear reasonable and, in the case of the base model, the parameter estimates are plausible. The fits to the egg deposition time series (Figure A2.2) indicate that the model captures the general pattern in the data, but does estimate egg depositions in the mid-1980's that are higher than the observed values. Fits to the smolt counts also capture the general pattern in the data, and, based on the model fits, indicate that smolt abundance in the 1980's was two to five times higher than at present. The fits to the juvenile abundance time series obtained by electrofishing (Figure A2.3) are poorer for the older age classes as would be expected given the cumulative effects of random variability (there is less than one year of mortality between the egg and age-0 life stage, whereas there are nearly three years between the egg stage and age-2 parr). The model estimates for age-0 parr in the early and mid-1980's are lower than the data, likely indicating that the model is producing abundance estimates that are influenced by the egg density data and the age-0 density data. Scatterplots of the abundance of Atlantic salmon within a cohort in sequential age classes (Figure A2.4) illustrate the asymptotic behaviour (characteristic of density dependence) for age-1 at relatively low densities of both age-0 and age-1 fish. However, most of the points have been obtained at low spawner abundance, making the estimation of carrying capacity difficult and potentially inaccurate. Although the estimated relationships appear to characterize the overall pattern in the data reasonably, the data do show considerable scatter around the fitted relationships.

The observed and estimated return rates of 1SW and 2SW salmon to the river mouth are shown in Figure A2.5. Because the observed rates are based on the observed adult abundance values divided by the observed smolt abundance values, and the estimated rates are based on the observed adult abundance values divided by the model estimates of annual smolt abundance, the differences in the observed and estimated rates is in the smolt abundance values (observed versus estimated) being used in their calculation. The 2005 smolt year is an outlier, but the model estimates a higher smolt abundance than was observed in that year (Figure A2.2) consistent with the higher age-1 parr density in 2004 (Figure A2.3). Although the model estimates do differ from the observed values, they take advantage of all of the available data, so they may be better estimates than those calculated directly from the observed smolt and adult time series. Both the 1SW and 2SW return rates show marked increases in the mid-1980's coincident with the closure of the commercial fisheries on Nova Scotia's coast. Return rates to Morgans Falls (Figure A2.6) were lower than to the river mouth in the earlier time periods, showing the effect of retention recreational fisheries, but the rates are more similar in recent years.

MCMC diagnostic plots for estimated and derived model parameters are shown in Figures A2.7 to A2.10. In general, the trace plots (second column from left) appear reasonable, and do not show significant autocorrelation (third column from left). Minima appear reasonably defined by the OFV for all model parameters (right column). As shown by the comparison of the marginal probability densities with the maximum likelihood estimates (MLE) (left column), the probability densities for a few model parameters are relatively skewed. In some cases (e.g. M_{parr}, Figure A2.7, second row from bottom), the skewness is not that large and is exacerbated by the plotting scale. However, in the case of R_{asy}, the mode of the marginal probability density is about two thirds that of the MLE. This difference carries over into the derived parameters for the carrying capacity for smolt in both the earlier and later time periods (Figures A2.8, bottom two rows), as well as the estimated equilibrium abundance in the early time period (Figure A2.10, top row). Although not shown here, the α and R_{asy} parameter values are highly negatively correlated and many of the lower R_{asy} values are paired with implausibly high values of α. The modes of the posterior probability densities for the lifetime EPS values for both time periods match the MLE's well (Figure A2.9).

Overall, the base model produces parameter estimates are near the middle of the range of parameter values produced by the five model runs shown here (Table A2.6). The base model has a statistically better fit to the data than the other model runs with the exception of Model 3. However, in our opinion, the better fit for Model 3 results from better agreement between the egg depositions and the lower fry densities, which is a sampling artifact resulting from the inclusion of several sites with zero densities that occurred when sampling was expanded to determine the range over which colonization had occurred. For this reason, Model 3 was not chosen as the base model. With the exception of R_{asy}, which is about 1.5 times higher for Model 3 than the base model, estimated parameter values are similar.

Maximum lifetime reproductive rates vary somewhat among model runs (Table A2.6). For the 1980's, the estimated rates vary from a value of 3.55 to 5.56 spawners per spawner. For the 2000's, they vary from 0.76 to 1.22, with the higher values coming from model runs where the smolt age composition is used to determine the smolt proportions-at-age. However, even these higher values are low enough that populations would have little capacity to compensate for the effects of environmental perturbations (floods, droughts, years of lower at-sea survival), and do not alter the conclusion that that these populations are expected to extirpate in the absence of human intervention or environmental change.

Further discussion of the parameter values and their implications for recovery planning is presented in the main text (Sections 2.2 and 2.5).

Table A2.1. Scale samples collected for aging from spawning salmon at the Morgans Falls fishway on the Lahave River (from Hubley 2010).

	Small salmon (<63 cm)		Large salmon (>63 cm)	
Decade	Number sampled	Percent of run sampled	Number sampled	Percent of run sampled
1970's	749	12.0	209	24.9
1980's	3694	16.8	2953	51.4
1990's	4136	36.3	2223	94.2
2000's	2361	45.8	1015	97.4

Table A2.2. Spawning escapement for 1SW and 2SW Atlantic salmon, and the egg deposition time series used for inputs for the LaHave River (above Morgans Falls) population dynamics models. The proportion of the large salmon component (which includes repeat-spawners) that are 2SW salmon, as well as the proportions of large and small salmon that are of wild origin, based on sampling of the adult population at Morgans Falls fish ladder, are also shown.

				Proportions		
Year	1SW	2SW	Egg deposition (millions)	2SW in the large component	Small that are wild	Large that are wild
1975			0.592			
1976			0.917			
1977			1.482			
1978			1.819			
1979	856	45	2.576	0.67	0.45	0.40
1980	1,648	251	4.378	0.86	0.83	0.36
1981	1,880	280	4.904	0.71	0.61	0.60
1982	804	85	3.462	0.33	0.56	0.52
1983	1,118	134	2.303	0.62	0.98	0.69
1984	2,041	322	3.307	0.83	0.89	0.92
1985	1,348	530	3.834	0.81	0.93	0.89
1986	1,584	365	4.578	0.62	0.92	0.88
1987	2,491	333	5.619	0.63	0.82	0.87
1988	2,465	229	5.339	0.57	0.70	0.86
1989	2,053	329	5.339	0.62	0.82	0.57
1990	1,866	215	4.066	0.54	0.76	0.78
1991	499	164	1.730	0.68	0.82	0.73
1992	1,950	153	3.375	0.71	0.76	0.78
1993	788	94	1.662	0.70	0.67	0.57
1994	641	83	1.632	0.66	0.76	0.52
1995	577	126	1.372	0.87	0.61	0.63
1996	735	87	1.604	0.75	0.65	0.58
1997	303	43	0.946	0.65	0.68	0.50
1998	720	38	1.334	0.54	0.78	0.50
1999	318	79	1.076	0.81	0.70	0.66
2000	502	52	1.425	0.78	0.63	0.56
2001	189	90	1.614	0.89	0.50	0.55
2002	423	15	1.842	0.39	0.37	0.54
2003	231	91	1.945	0.92	0.53	0.48
2004	313	55	1.953	0.82	0.49	0.54
2005	224	34	1.143	0.73	0.57	0.52
2006	418	64	1.131	0.78	0.98	0.69
2007	341	32	0.561	0.89	1.00	0.85
2008	593	91	1.078	0.93	1.00	1.00
2009	168	42	0.474	0.80	1.00	1.00
2010	300	44	0.687	0.84	1.00	1.00

Table A2.3. Recreational catches for the LaHave River, 1979 to 2000.

Year	Season	Catch (small)	Retained (small)	Released (small)	Catch (large)	Retained (large)	Released (large)	Effort (rod days)
1979	open	1,365	1,365	0	107	107	0	5,505
1980	open	1,273	1,273	0	520	520	0	10,554
1981	open	1,637	1,637	0	442	442	0	16,417
1982	open	785	785	0	180	180	0	14,450
1983	open	299	271	28	221	209	12	10,916
1984	open	1,502	1,357	145	293	124	169	10,333
1985	open	1,869	1,684	185	993	0	993	10,044
1986	open	2,108	1,838	270	948	0	948	12,932
1987	open	2,921	2,543	378	461	0	461	12,342
1988	open	1,688	1,551	137	316	0	316	11,863
1989	open	2,925	2,506	419	686	0	686	13,354
1990	open	2,488	2,099	389	607	0	607	14,046
1991	open	285	240	45	146	0	146	4,349
1992	open	1,144	1,040	104	184	0	184	8,892
1993	open	1,105	907	198	238	0	238	10,106
1994	open	166	142	24	122	0	122	4,459
1995	open	646	566	80	244	0	244	6,362
1996	open	1,599	1,149	450	345	0	345	8,874
1997	open	428	385	43	185	0	185	4,081
1998	closed	0	0	0	0	0	0	0
1999	open	59	3	56	40	0	40	448
2000	closed	0	0	0	0	0	0	0
2001	open	88	0	88	61	0	61	288
2002	open	201	0	201	43	0	43	389
2003	open	154	0	154	113	0	113	573
2004	open	121	0	121	34	0	34	325
2005	open	165	0	165	61	0	61	599
2006	open	211	0	211	65	0	65	476
2007	open	94	0	94	23	0	23	497
2008	open	29	0	29	12	0	12	209
2009	open	63	0	63	14	0	14	345
2010	closed	0	0	0	0	0	0	0

Table A2.4. Smolt abundance in the LaHave River (above Morgans Falls) from 1996 to 2010; and the number of smolts by age class from scale samples collected during smolt monitoring (1996 to 2010), as well as from the number-at-age from scale samples of returning 1SW and 2SW adults (1975 to 2009).

		Number at age based on adult characteristics			Number at age based sampling of the smolt run		
Year	Abundance	Age-2	Age-3	Age-4	Age-2	Age-3	Age-4
1975		46	0	0			
1976		63	0	0			
1977		29	3	0			
1978		198	10	0			
1979		214	6	0			
1980		220	30	0			
1981		107	4	0			
1982		202	3	0			
1983		340	7	0			
1984		412	31	0			
1985		399	61	1			
1986		628	38	0			
1987		703	42	1			
1988		796	131	0			
1989		704	102	1			
1990		269	72	0			
1991		832	187	1			
1992		303	67	0			
1993		213	34	0			
1994		201	56	2			
1995		177	46	1			
1996	20,511	142	41	0	64	35	12
1997	16,525	317	59	2	33	8	0
1998	15,600	174	17	0	192	48	0
1999	10,420	219	40	0	154	20	1
2000	16,338	78	25	0	388	238	7
2001	15,693	207	21	0	418	27	0
2002	11,860	108	19	0	366	94	0
2003	17,845	81	22	0	220	97	0
2004	20,613	199	66	0	186	118	1
2005	5,260	287	94	1	110	48	0
2006	22,971	350	61	1	292	30	0
2007	25,430	487	143	0	319	106	0
2008	14,450	177	34	0	1076	159	4
2009	8,644	132*	33*	0*	484	125	0
2010	16,215				548	135	3

*Based on 1SW age structure only.

Table A2.5. Annual mean densities of juvenile Atlantic salmon by age class in the LaHave River (above Morgans Falls) used as inputs for the population dynamics model. Three variants of the data are used: "GLM / <2 yr / reg." values are standardized with a generalized linear model with "site" and "year" as factors to correct for the effects of changes in the sites included in the survey each year, and are estimated using only sites that were fished in more than two years and using a regression-based method to derive the proportions-at-age for parr; "GLM / <2 yr / l.f." values are derived similarly except the proportions-at-age were determined by visual examination of the length frequency data at each site; and "No GLM / all / l.f." values are un-standardized annual means calculated using data from all sites and proportions-at-age determined by visual examination of the length frequency data.

	GLM / <2yr / reg.			GLM / <2yr / l.f.			No GLM / all / l.f.		
Year	Age-0	Age-1	Age-2	Age-0	Age-1	Age-2	Age-0	Age-1	Age-2
1978	26.14			26.14	6.33	0.52	18.21	6.26	0.51
1979	34.29	2.81	0.01	34.29	2.69	0.13	21.86	2.28	0.11
1980	60.34			60.34			29.44		
1981	92.72	6.30	0.48	92.72	6.23	0.55	46.28	6.11	0.54
1982	31.89			31.89			23.16		
1983	36.10	5.62	0.14	36.10	5.48	0.29	17.57	5.38	0.28
1984	37.16	7.67	0.59	37.16	6.64	1.62	26.76	4.47	1.09
1986	3.32			3.32			9.36		
1987	60.40			60.40			50.18		
1988	28.85			28.85			23.44		
1991	21.03	4.81	0.25	21.03	4.62	0.43	11.65	6.61	0.62
1992	19.83	18.91	0.41	19.83	18.86	0.45	10.60	16.90	0.41
1993	26.63	9.37	0.23	26.63	9.34	0.26	16.47	10.77	0.29
1994	10.56	5.41	0.41	10.56	5.51	0.31	7.81	5.08	0.29
1995	8.70	5.40	0.61	8.70	5.59	0.42	3.96	7.09	0.54
1997	3.92	9.46	0.57	3.92	9.12	0.91	2.33	8.88	0.89
1998	5.64	10.24	0.22	5.64	9.68	0.78	4.38	9.48	0.77
1999	9.96	9.25	0.47	9.96	8.34	1.37	9.36	7.88	1.30
2000	6.01	11.85	0.36	6.01	11.14	1.07	4.37	10.94	1.05
2001	13.81	15.27	0.23	13.81	13.39	2.11	10.05	13.15	2.07
2002	3.61	4.51	0.22	3.61	4.16	0.57	13.83	2.72	0.38
2003	0.81	4.65	0.24	0.81	4.71	0.18	0.48	4.87	0.19
2004	9.87	2.47	0.49	9.87	2.15	0.80	7.19	2.12	0.79
2005	7.52	8.11	0.30	7.52	7.58	0.84	5.47	7.44	0.82
2006	2.73	4.54	0.43	2.73	3.64	1.33	2.32	3.47	1.27
2007	4.83	5.70	0.90	4.83	5.67	0.92	4.54	5.36	0.87
2008	3.87	1.82	0.24	3.87	1.86	0.21	3.65	1.69	0.19
2009	5.09	0.97	0.55	5.09	1.33	0.19	4.78	1.26	0.18
2010	5.18	3.08	0.38	5.18	3.16	0.31	4.87	2.98	0.29

Table A2.6. Maximum likelihood estimates (standard errors) for life history parameters for the LaHave River (above Morgans Falls) Atlantic salmon population obtained from five versions of the dynamics model. Variations on the electrofishing data are explained in the caption for Table A2.5. "Past" and "Present" refer to the 1980-89 and 2000-2009 time periods, respectively.

Model	Base	Model 2	Model 3	Model 4	Model 5
Assumptions:					
Electrofishing data:	glm / lf / >2yr	glm / reg / >2yr	no glm / lf / all	glm / lf / >2yr	no glm / lf / all
Smolt age composition data:	adult	adult	adult	smolt	smolt
OFV:	1822.1	1858.2	1808.1	701.3	704.2
Freshwater production:					
M_{Egg}	0.88 (0.04)	0.50 (0.13)	0.91 (0.03)	0.81 (0.05)	0.74 (0.08)
α	0.58 (0.07)	0.61 (0.08)	0.73 (0.09)	1.00 (0.00)	0.90 (0.14)
R_{asy}	35.53 (12.53)	35.84 (15.41)	50.59 (30.74)	21.71 (4.46)	16.61 (3.12)
M_{Parr}	0.72 (0.07)	0.90 (0.02)	0.73 (0.06)	0.83 (0.03)	0.84 (0.03)
j_2 past	0.83 (0.04)	0.67 (0.04)	0.82 (0.04)	0.67 (0.07)	0.62 (0.09)
j_3 past	1.00 (0.00)	1.00 (0.00)	1.00 (0.00)	1.00 (0.00)	1.00 (0.00)
j_2 present	0.60 (0.06)	0.34 (0.04)	0.58 (0.06)	0.39 (0.05)	0.39 (0.05)
j_3 present	0.99 (0.01)	0.97 (0.02)	0.99 (0.01)	0.91 (0.03)	0.91 (0.03)
electrofishing scalar (*h*)	16,832 (5,544)	83,145 (20,806)	18,567 (5,957)	39,667 (10,783)	39,509 (10,976)
Egg to smolt dynamics:					
$\breve{\alpha}$ past	0.02 (0.00)	0.02 (0.00)	0.02 (0.00)	0.02 (0.00)	0.03 (0.00)
$\breve{R}_{asy}$ past	147,700 (55,506)	212,130 (97,100)	217,110 (136,020)	103,720 (24,376)	73,016 (17,433)
$\breve{\alpha}$ present	0.01 (0.00)	0.01 (0.00)	0.01 (0.00)	0.02 (0.00)	0.02 (0.00)
$\breve{R}_{asy}$ present	119,690 (44,762)	120,320 (54,365)	172,390 (107,770)	69,182 (13,494)	51,071 (10,943)
Return Rates:					
1SW average (1980-1989)	7.28 (0.85)	7.12 (0.84)	7.75 (0.91)	6.92 (0.81)	7.11 (0.87)
1SW average (2000-2009)	2.25 (0.20)	2.23 (0.20)	2.22 (0.20)	2.37 (0.21)	2.39 (0.21)
2SW average (1980-1989)	0.74 (0.09)	0.67 (0.08)	0.79 (0.09)	0.73 (0.09)	0.75 (0.10)
2SW average (2000-2009)	0.33 (0.03)	0.33 (0.03)	0.32 (0.03)	0.34 (0.03)	0.35 (0.03)
Lifetime egg production per smolt:					
average EPS (1980-1989)	217.55 (25.31)	209.62 (24.58)	231.69 (27.13)	208.33 (24.61)	214.28 (26.43)
average EPS (2000-2009)	63.03 (5.60)	63.01 (5.59)	62.07 (5.52)	66.37 (5.88)	67.14 (5.93)
Max. life. reproductive rate:					
average (1980-1989)	3.59 (0.50)	4.59 (0.69)	3.55 (0.51)	4.74 (0.56)	5.56 (1.05)
average (2000-2009)	0.84 (0.08)	0.78 (0.09)	0.76 (0.08)	1.01 (0.09)	1.22 (0.16)
Equilibrium egg abundance:					
average (1980-1989)	23,188,000 (6,760,900)	34,776,000 (13,359,000)	36,145,000 (19,696,000)	17,052,000 (2,650,500)	12,834,000 (1,622,900)
average (2000-2009)	-1,398,700 (1,285,100)	-2,108,500 (1,860,100)	-3,457,300 (3,376,900)	35,792 (423,610)	616,920 (277,280)
Equilibrium smolt abundance:					
average (1980-1989)	106,590 (36,012)	165,910 (70,952)	156,000 (91,107)	81,855 (18,133)	59,893 (12,794)
average (2000-2009)	-22,190 (20,553)	-33,462 (29,741)	-55,698 (54,661)	539 (6,380)	9,188 (4,168)

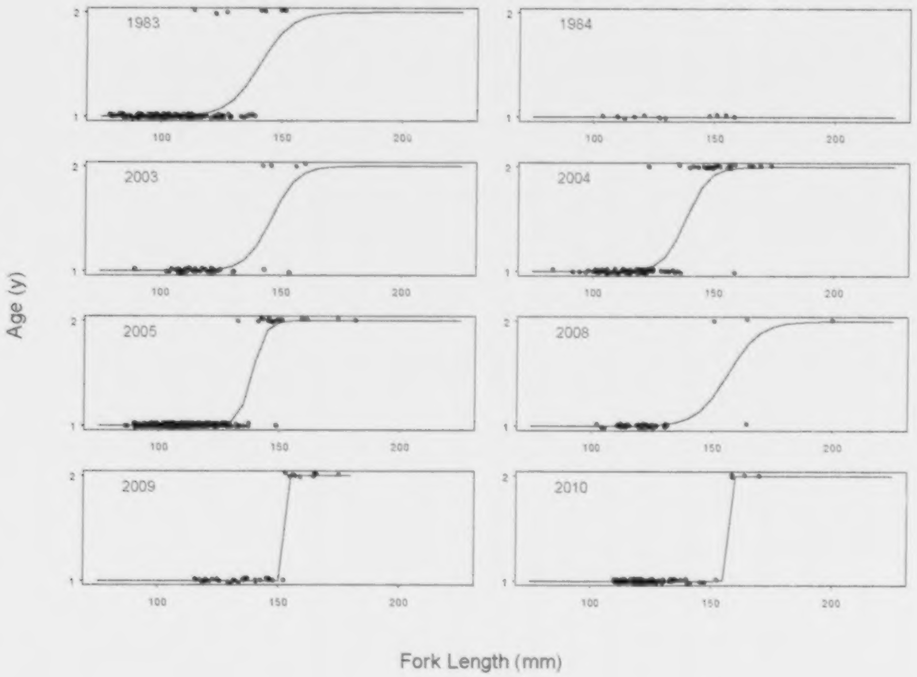

Figure A2.1. Length frequency keys used to determine the proportions of age-1 and age-2 parr for the LaHave River (above Morgans Falls) population for eight years. The average of these functions was used for the other years shown in Table A2.5.

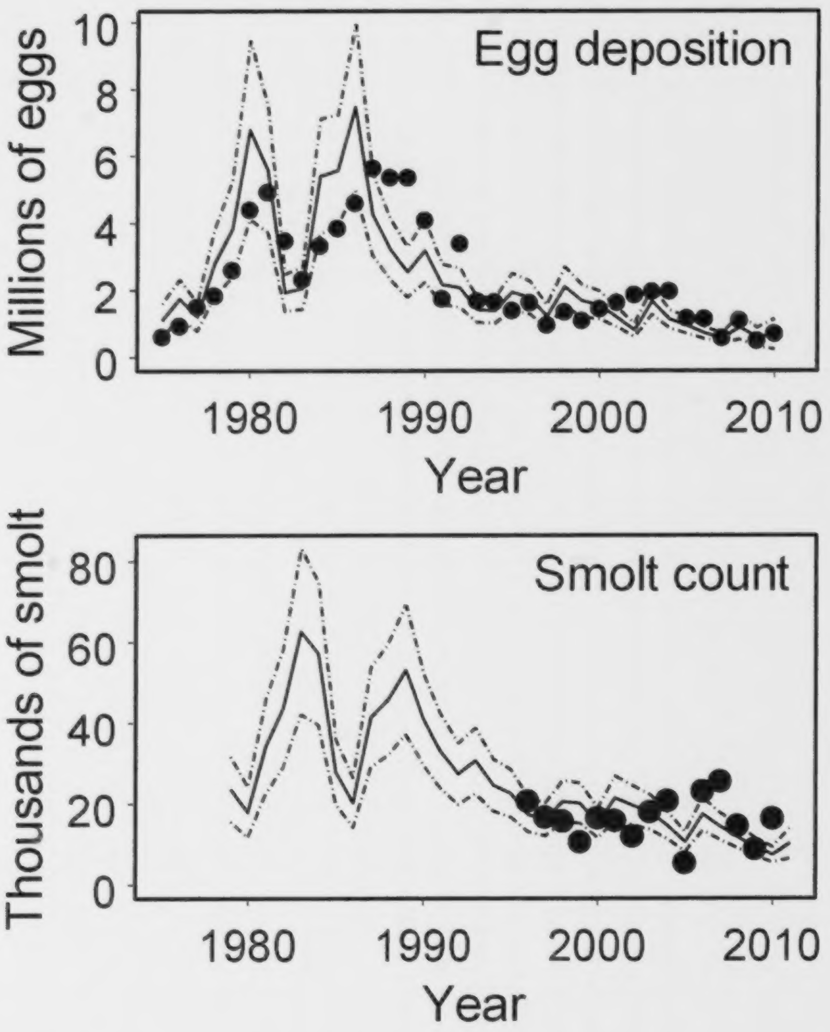

Figure A2.2. Observed (points) and estimated (solid lines) egg depositions (top panel) and smolt counts (bottom panel) from the base population dynamics model run for the LaHave River (above Morgans Falls) Atlantic salmon population. The dashed lines show 95% confidence intervals based on normal approximations.

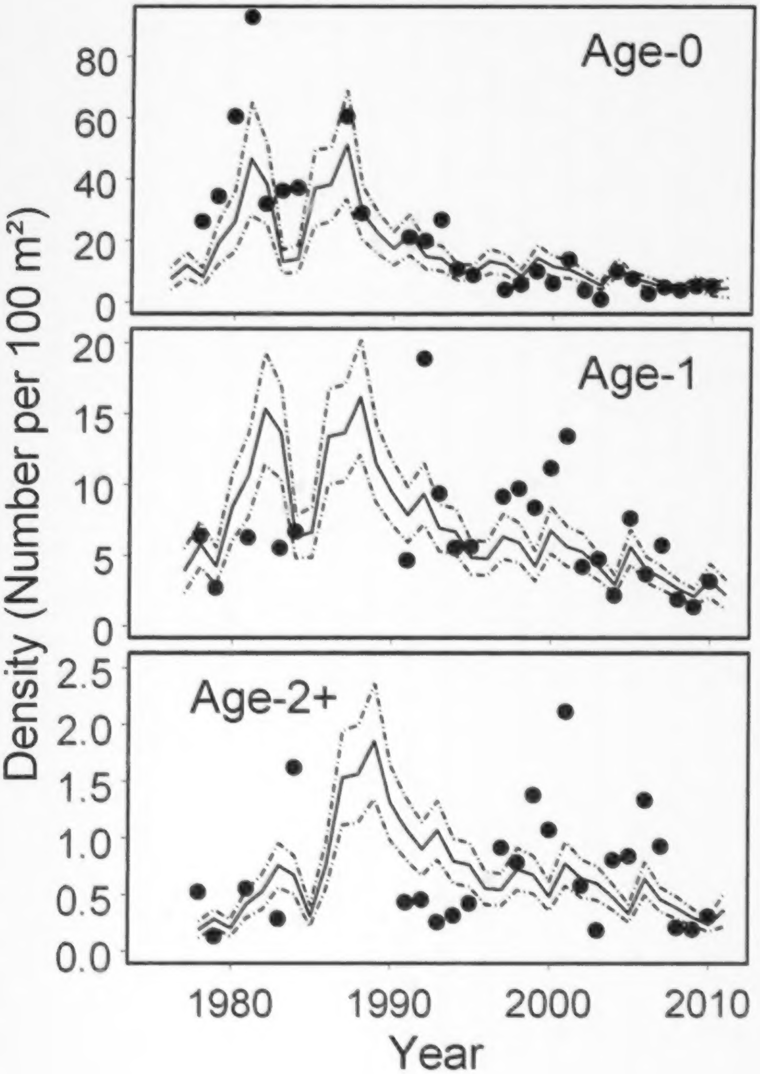

Figure A2.3. Observed (points) and estimated (solid lines) for age-0 (top panel), age-1 (middle panel) and age-2+ (bottom panel) juvenile salmon densities from the base population dynamics model run for the LaHave River (above Morgans Falls) Atlantic salmon population. The dashed lines show 95% confidence intervals based on normal approximations.

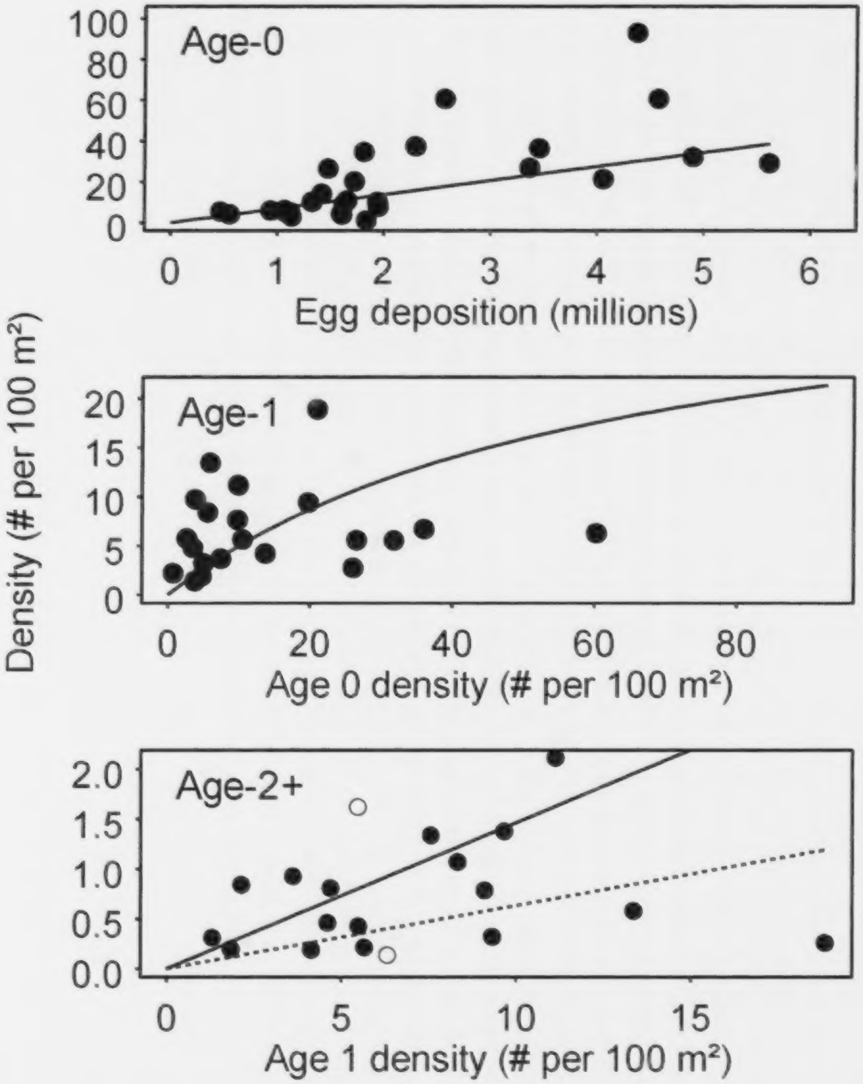

Figure A2.4. Functional relationships between the abundance of eggs, and the densities of age-0 , age-1 and age-2+ juvenile Atlantic salmon from the base population dynamics model run for the LaHave River (above Morgans Falls) Atlantic salmon population. The points show the data and the lines show the fitted relationships between age classes. The dashed line and open points in the bottom panel shows the data and model fit for the 1980's time period, whereas the filled points and solid line in this figure shows the fit for the 2000's time period.

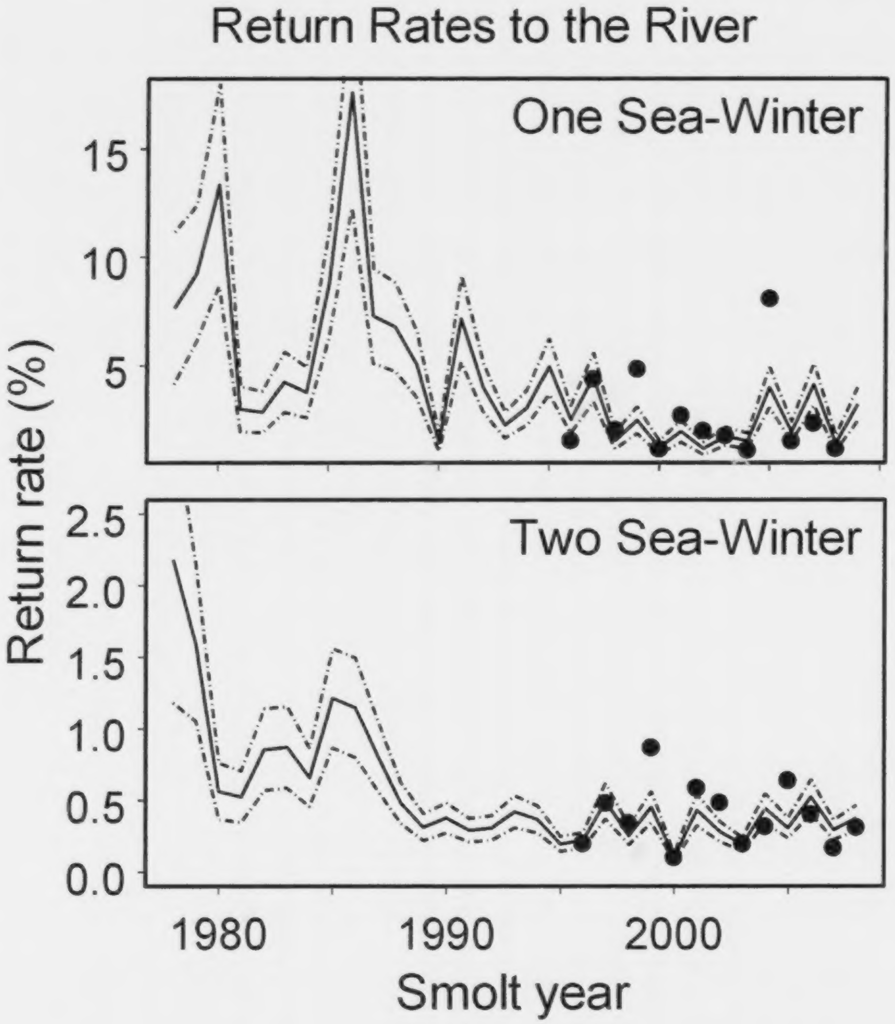

Figure A2.5. Observed (points) and estimated (solid lines) smolt-to-adult return rates to the river mouth (indicative of at-sea survival) for salmon returning as 1SW (top panel) and 2SW (bottom panel) adults. Estimates are obtained from the base population dynamics model run for the LaHave River (above Morgans Falls) Atlantic salmon population. The dashed lines show 95% confidence intervals based on normal approximations.

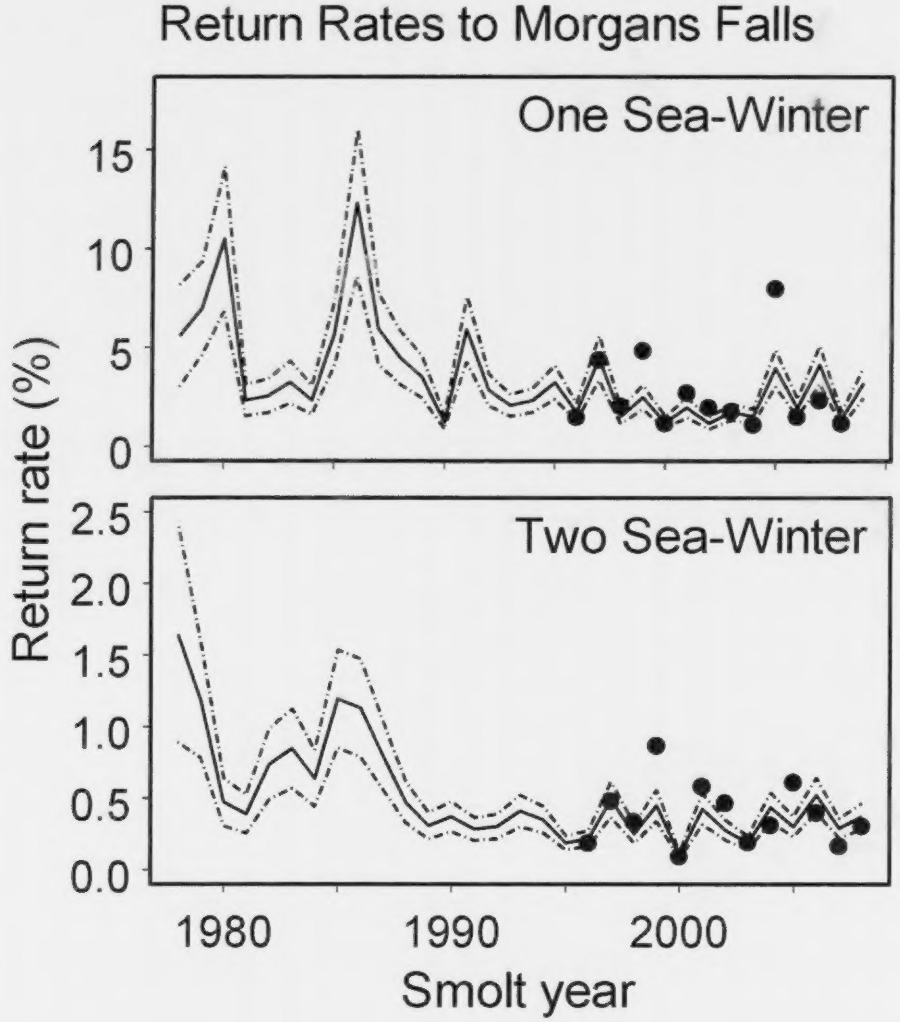

Figure A2.6. Observed (points) and estimated (solid lines) smolt-to-adult return rates to spawning escapement (indicative of the combined effects of at-sea survival and mortality from the recreational fishery) for salmon returning as 1SW (top panel) and 2SW (bottom panel) adults. Estimates are obtained from the base population dynamics model run for the LaHave River (above Morgans Falls) Atlantic salmon population. The dashed lines show 95% confidence intervals based on normal approximations.

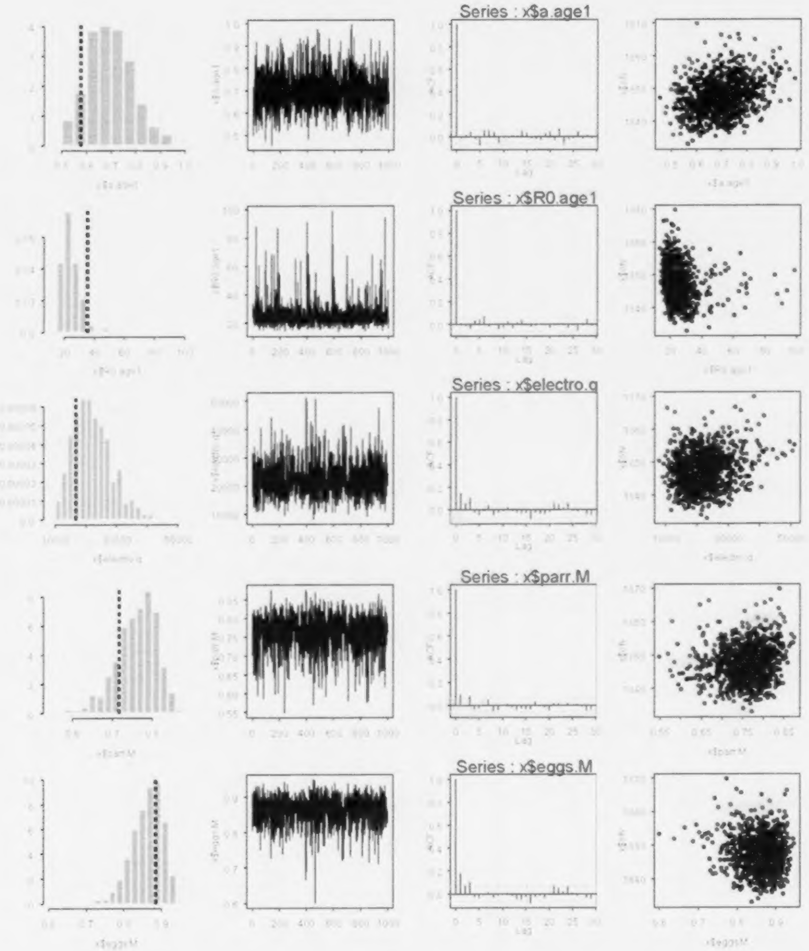

Figure A2.7. MCMC results for the freshwater production model survival parameters for the LaHave River (above Morgans Falls) base model run. The first column shows the probability density (the dashed lines are the maximum likelihood estimate, the second column shows the thinned chain, the third column shows the autocorrelation in the chain, and the fourth column is a plot of the objective function value versus the parameter value for each step in the MCMC chain.

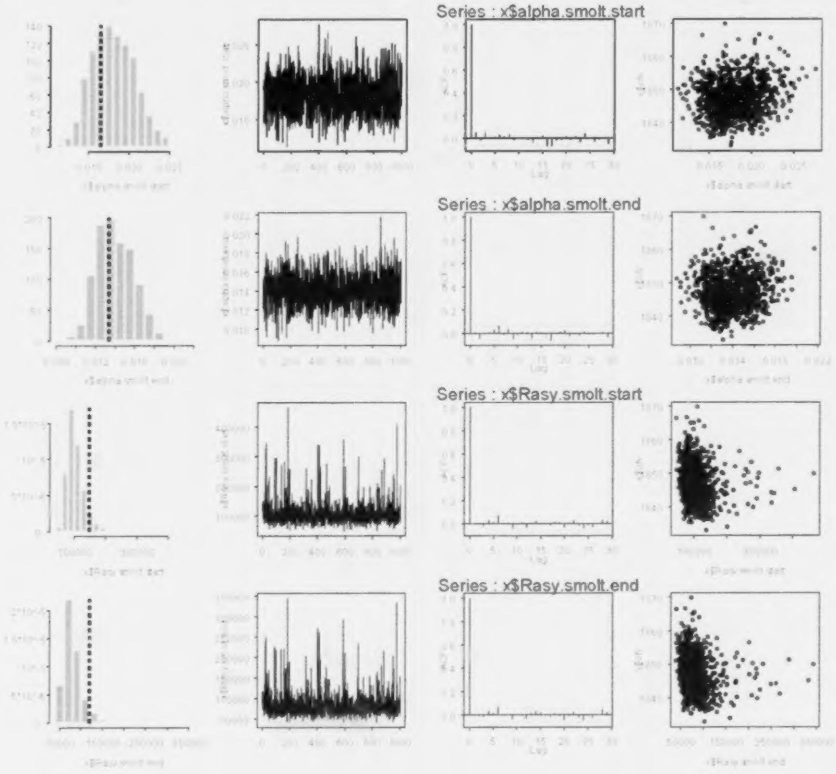

Figure A2.8. MCMC results for the four derived model parameters related to freshwater production for the LaHave River (above Morgans Falls) base model run: the egg-to-smolt Beverton-Holt alpha and asymptotic recruitment level values for the 1980's (start) and 2000's (end) time periods. The first column shows the probability density (the dashed lines are the maximum likelihood estimate), the second column shows the thinned chain, the third column shows the autocorrelation in the chain, and the fourth column is a plot of the objective function value versus the parameter value for each step in the MCMC chain.

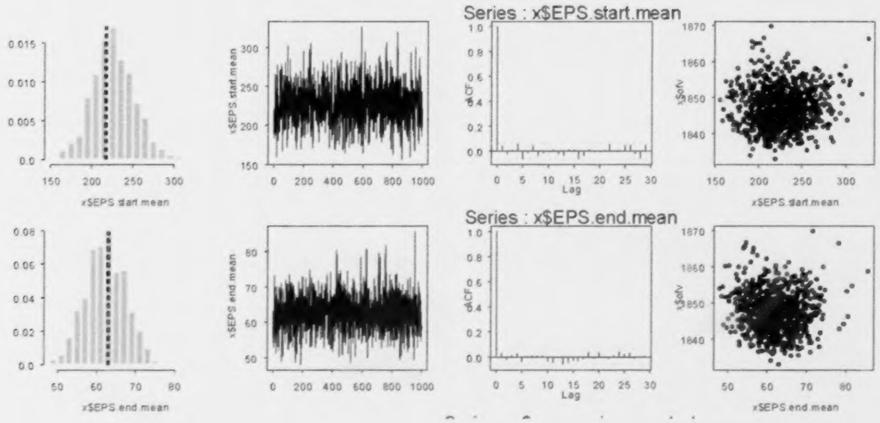

Figure A2.9. MCMC results for two derived model parameters for the LaHave River (above Morgans Falls) base model run: the mean lifetime EPS values for the 1980's (start) and 2000's (end) time periods. The first column shows the probability density (the dashed lines are the maximum likelihood estimate), the second column shows the thinned chain, the third column shows the autocorrelation in the chain, and the fourth column is a plot of the objective function value versus the parameter value for each step in the MCMC chain.

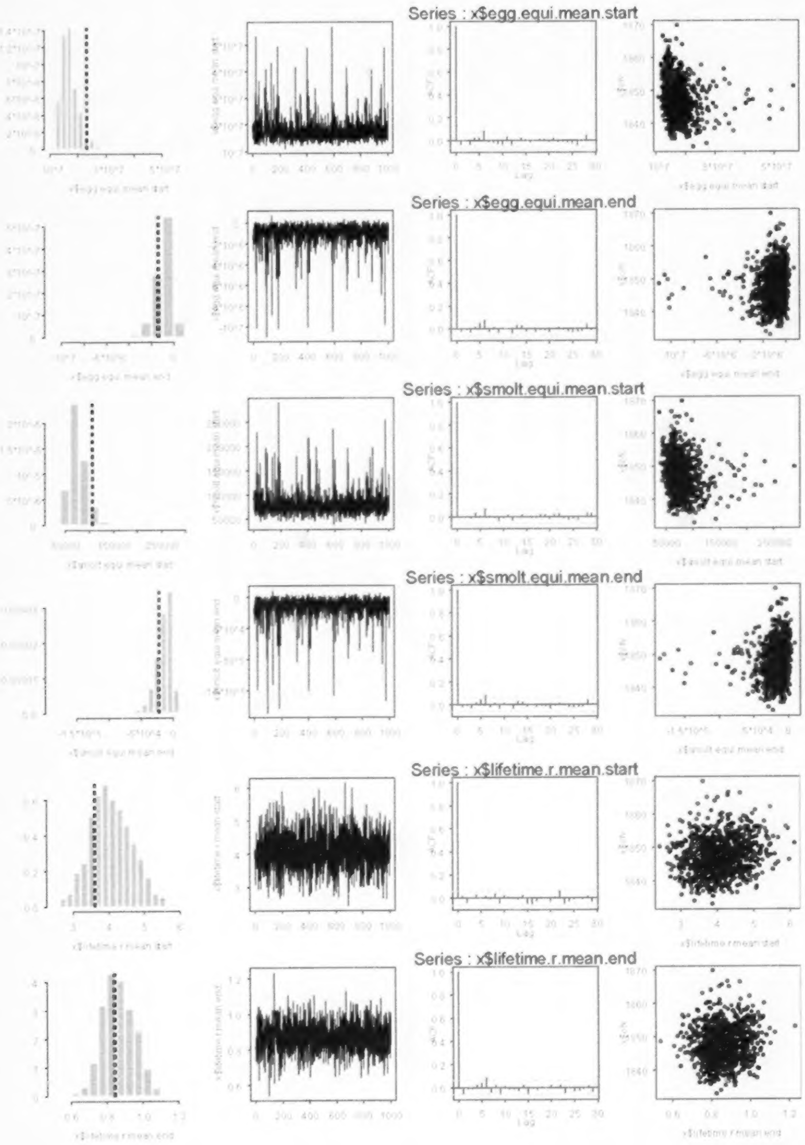

Figure A2.10. MCMC results for three derived model parameters (mean equilibrium abundance of eggs, mean equilibrium abundance of smolts, and maximum lifetime reproductive rate) for two time periods (start = 1980's; end = 2000's) for the LaHave River (above Morgans Falls) base model. The first column shows the probability density (the dashed lines are the maximum likelihood estimate), the second column shows the thinned chain, the third column shows the autocorrelation in the chain, and the fourth column is a plot of the objective function value versus the parameter values for each step in the MCMC chain.

APPENDIX 3. LIFE HISTORY PARAMETER ESTIMATION FOR THE ST MARY'S RIVER (WEST BRANCH) ATLANTIC SALMON POPULATION

The life history parameter estimates for the St. Mary's River (West Branch) Atlantic salmon population, provided in Section 2.2, as well as the information on the population's dynamics in Section 2.5, were derived using the statistical, life-history-based population dynamics model presented in Appendix 1. The application of the model to this population is described in this appendix. Included is a description of the data series used in the analyses, alternate model runs, interpretation of results, as well as the reasoning and biological justification for selecting the preferred model.

A3.1 Data

Recreational Fishery Statistics

Catch and effort data from the recreational fishery are collected using the same methods for all rivers in the Southern Upland region, as described in Appendix 2. Data for the St. Mary's River are provided in Table A3.1. The recreational fishery statistics are reported for the entire St. Mary's River, whereas the assessments are only for the West Branch population. Recreational fishing occurs on both the East and West branches, as well as downstream of their confluence. As was the case for the LaHave River, an assumption was made that a portion of the catch and harvests are of fish destined for the West Branch. As with the LaHave example, the proportion of the total habitat in the watershed that is located above West Branch (55%) was used to split the catch and a hook-and-release mortality estimate of 4% was assumed, consistent with recent assessments (e.g. DFO 2011).

For the St. Mary's River (West Branch) population, the recreational fishery statistics are used differently than they were for the LaHave. Here, they are first used to estimate abundance in the years from 1974 to 1997 (see below). These abundance estimates are then used to derive the egg deposition time series prior to 1997, and also to estimate the smolt-to-adult return rates to both the mouth of the river and to spawning escapement as described in Appendix 1 (equations in Table A1.4).

As is shown in the Results Section, life history parameter estimates for the 2000's time period are not overly dependent on the assumptions used to derive adult abundance and egg deposition prior to 1997. One alternate model does not use these data (Model 2). However, the estimates of past abundance of adults and smolts, as well as return rates and population dynamics, do depend on the recreational catch as a data input.

Adult Abundance and Biological Characteristics

The adult abundance time series for the St. Mary's River (West Branch) salmon population is derived from two sources. Since 1997, the number of large and small salmon in the West Branch has been estimated using mark-recapture experiments (Gibson et al. 2009a). These surveys take place after the recreational fishing season closes and shortly before spawning, and are intended to estimate annual spawning escapement. The surveys have not been successfully completed in all years, usually due to flow conditions, necessitating some extrapolation to obtain estimates. Details are provided in the Bowlby et al. (2013a).

Prior to 1997, the only data available for estimating adult abundance are the recreational fishery statistics described above. These data have been used to estimate abundance in past assessments. However, these estimates are partially dependent on the assumed catch rate of the recreational fishery, which cannot be calculated directly for the St. Mary's River. O'Neil and Harvie (1995) and O'Neil et al. (1997b) estimated adult abundance using an assumed recreational catch rate of 0.3, a value similar to the long-term average catch rate on the LaHave River (Amiro and Jefferson 1997). O'Neil et al. (1997a) proposed that the annual catch rate from the LaHave River could be used as an alternative to the constant value and O'Neil et al. (1998) provided a time series of the recreational catch rates from the LaHave (derived for hatchery salmon and the correct series was not provided – see Amiro and Jefferson (1998) for the correct series) that could be used for this purpose.

For the analyses here, we estimated the abundance from the recreational fishery statistics using three methods: assuming a catch rate of 0.3, using the catch rates for large and small salmon estimated using the LaHave model (Appendix 2), and following the suggestion of O'Neil et al. (1998), using the catch rates for the LaHave River presented in Amiro and Jefferson (1998). The three resulting spawning escapement time series are provided in Table A3.2. Note that these derivations only apply to the years prior to 1997. The values used from 1997 onwards are those obtained from the mark-recapture experiment to estimate abundance and are the same in the three series.

The proportion of virgin 1SW and 2SW salmon in the population from 1998 to 2010, as well as the proportion of repeat spawners and the proportion of virgin 2SW salmon in the large salmon component are shown in Table A3.3. This population is comprised almost entirely of 1SW salmon. The annual values are used in the model for 1998 to 2010, whereas the average of these values is used for the years before 1998.

As was the case for the LaHave model, the adult counts and biological characteristics are used for three purposes. First, these data are used to estimate annual egg deposition (described below). Second, the data are used to determine the number of 1SW and 2SW first-time spawning salmon that survive to spawn. Lastly, these estimates are then used to calculate the smolt-to-adult return rates to the river mouth and to the spawning escapement as described in Appendix 1 (equations in Table A1.4).

There is relatively little information available about the repeat spawning dynamics of salmon in the St. Mary's River (West Branch) population. Therefore, the analysis for the LaHave River population was used (see Section 2.4) to characterize this component of the St. Mary's River (West Branch) population.

Egg Deposition Time Series

Annual egg depositions were calculated from each of the spawning escapement time series using average fecundities of small and large salmon, 1,818 and 5,803 eggs per fish, respectively. These values were calculated using the biological characteristics of St. Mary's River (West Branch) salmon from samples collected during the mark-recapture experiments (Table A3.4) and the length-fecundity relationship developed for LaHave River salmon (Cutting et al. 1987):

$$\text{Fecundity}=446.54*e^{(0.0362*FL)}.$$

The egg deposition time series used in the model are shown in Figure A3.1 and are provided in Table A3.2. The series are relatively similar from 1990 to present and are identical from 1997 onwards. The egg deposition time series based on the assumed catch rate of 0.3 is the lowest in the early 1980's but is the middle series for most years in the 1970's and from 1986 onwards.

Smolt Abundance and Biological Characteristics

The annual smolt migration for the St. Mary's River (West Branch) salmon population was monitored from 2005 to 2009 via a smolt wheel installed at the Glenelg bridge (Gibson et al. 2009a). Abundance estimates are obtained via a mark-recapture experiment in which a portion of the smolts are tagged, transported upstream about 1 km and released back into the river. Capture efficiencies at the wheel have ranged from 0.028 to 0.103; the higher value was obtained in a year when two wheels were fished side by side. Weight and fork length information is collected from a portion of the smolts captured each year, and scale samples are collected to determine their age. Most smolts are age-2. The abundance estimates and the number of sampled smolts in each age class are used as model inputs and are provided in Table A3.5.

Abundance of Fry and Parr

The relative abundance of age-0 (fry), age-1 and age-2+ (collectively known as parr) juvenile salmon in the St. Mary's River is determined by electrofishing. As in the LaHave example (Appendix 2), the notation 2+ is used to denote a plus group consisting of all parr age-2 and older, consistent with the way this notation is used for other species (Quinn and Deriso 1999). In these analyses, only data collected from sites in the West Branch are used. Originally, electrofishing surveys roughly followed a random-stratified design for site selection (Amiro et al. 1989, Amiro 1993), a method for site selection thought to give a more unbiased estimator of mean annual density because sampling takes place over the range of habitat types (Gibson et al. 2008a), although site selection did vary from year to year.

As detailed in Appendix 2, site selection was not fixed *a priori* for the electrofishing surveys, which can lead to bias in the resulting density estimates if the proportions of high and low density sites change annually or systematically over time. Each year, between three and nine (out of a maximum of 30 sites) were electrofished on the West Branch of the St. Mary's River. As was done for the LaHave River, standardized density series were obtained from a generalized linear model (GLM) using 'site' and 'year' as factors, assuming a Poisson error distribution. We chose to test two alternate time series in the freshwater component of the population dynamics model: the estimates of age-0, age-1 and age-2+ density that are reported annually for the St. Mary's River (e.g. Gibson et al. 2009a), as well as the standardized series derived using the GLM. These time series are provided in Table A3.6.

A3.2 Model Formulations

The model was set up using data from 1974 to 2010. The estimated demographic parameters for the freshwater production model are listed in Table A3.7. These include the annual mortality rates of eggs and parr (M_{Egg} and M_{Parr}), the maximum rate of population increase for age-1 parr (α), the carrying capacity for age-1 parr (R_{asy}), and the smoltification probability at age-2 (j_2). Similar to the analysis for the LaHave River, we estimated annual egg deposition and attempted to use a step function to split the model into two halves so that changes in freshwater productivity could be evaluated. Using the step function, we could not obtain reasonable model fits and parameter estimates. In particular, we could not estimate R_{asy} for the recent period when abundance is low (this is evident in Model 2, see below). Although the timing and magnitude of changes in life history parameters are almost certainly variable, maximum likelihood estimates representative of the full time period are provided from the analysis.

There are very few parr or smolt older than age-2 in the St. Mary's River (West Branch). For this reason, estimation of the electrofishing scalar, h, and the mortality rates for eggs, M_{egg}, and parr, M_{parr}, are confounded, and for this reason an alternate method was needed in order to determine h. We therefore fixed h at a value of 14,162, thereby setting the ratio of the total number of parr in the population to the density of parr estimated in an electrofishing to the value obtained for the LaHave population, based on the idea that the electrofishing surveys were originally designed using the same principles, and therefore should be similarly representative. Changing this value does not change the overall dynamics, but does change how mortality is partitioned among age classes. Increasing h decreases the estimate of M_{egg} and increases the estimate M_{parr}, and vice versa, but the total mortality from the egg to the smolt stage remains more or less unchanged.

We selected a base model run that consisted of using the standardized electrofishing time series and the past adult abundances calculated from an assumed exploitation rate of 0.3, and fitting the model to all data from 1974 to 2010. In total, 40 parameters were estimated in this model. Examples of other model runs are shown in Table A3.7, including:

- Model 2: similar to the base model but using data from 1997 to 2010 only;
- Model 3: similar to base model but using the un-standardized electrofishing data;
- Model 4: similar to the base model but using the past abundance estimates derived using annual exploitation rates from the LaHave River;
- Model 5: similar to the base model but using the past abundance estimates derived using the annual exploitation rates from hatchery salmon in the LaHave River.

Consistent with Gibson et al. (2008c) and with the LaHave model, we found that estimating the annual egg depositions, rather than using the data as constants in the model, improved the model fit.

The relative contribution of each likelihood to the objective function value (OFV) can be controlled using a set of weighting values. These values may be selected to keep any one part of the objective function from dominating the fit, or alternatively, to reflect perceptions of data accuracy (Merritt and Quinn 2000). As is the case for the LaHave model, for the St. Mary's all weights equal were set to one, an approach that has the advantage that the OFV can be interpreted as the likelihood.

Several other data combinations and likelihood weighting combinations were evaluated as well. Although the parameter estimates varied slightly in each case, none of these other model runs altered the conclusion that the dynamics exhibited in the base model are the best approximation of the dynamics of the St. Mary's River (West Branch) population at this time.

A3.3 Results

Parameter estimates from the model are given in Table A3.7 and model fits and diagnostic plots for the base model are shown in Figure A3.2 to A3.9. Overall, the model fits to the data appear reasonable and, in the case of the base model, the parameter estimates are plausible. The very good fit to the egg deposition time series (Figure A3.2) is a bit misleading because there is no other data to contribute to its estimation before 1990. The differences in the fits among models arise primarily from how closely the egg deposition data match the age-0 data in the early 1990's. Fits to the smolt counts capture the general pattern in the data. The estimated abundance of smolts in the 1980's is four to eight times the estimated smolt abundance in the late 2000's. As expected, the fits to the juvenile abundance time series obtained by electrofishing (Figure A3.3) are poorer for the older age classes given the cumulative effects of random variability, but in general the model estimates capture the overall pattern in the data better than in the LaHave population. Scatterplots of the abundance of parr within a cohort in sequential age classes (Figure A3.4) illustrate the asymptotic behaviour (characteristic of density dependence) for age-1 at relatively low densities of both age-0 and age-1 fish. Although the estimated relationships appear to characterize the overall pattern in the data reasonably, the data do show scatter around the fitted relationships.

The observed and estimated return rates of 1SW and 2SW salmon to the river mouth are shown in Figure A3.5. The differences between the estimated rates and the observed rates result only from the different smolt abundance values (observed versus estimated) going into the model because the number of adults is the same in the both cases. As was the case for the LaHave population, both the 1SW and 2SW return rates show increases in the mid-1980's coincident with the closure of the commercial fisheries on Nova Scotia's coast. Also similar to the LaHave, return rates to spawning escapement (Figure A3.6) were lower than to the river mouth in the earlier time periods, showing the effect of retention recreational fisheries, but the rates are more similar in recent years. However, in this instance, the difference in the return rates to the river mouth and to spawning escapement result from the assumed exploitation rates used to estimate past abundance, a model assumption rather than an analytical result.

MCMC diagnostic plots for estimated and derived model parameters are shown in Figures A3.7 to A3.9. In general, the trace plots (second column from left) appear reasonable, and do not show significant autocorrelation (third column from left). Minima appear reasonably defined by the OFV for all model parameters (right columns). The comparisons of the marginal probability densities with the maximum likelihood estimates (left columns) indicate very good agreement between these measures of central tendency.

Overall, the base model produces parameter estimates that are in the middle of the range of parameter values produced by the five model runs shown here (Table A3.7). Both Models 4 and 5 have statistically better fits to the data than the base model (not significant for Model 4), but we choose Model 1 as the base model because: (1) the assumption of a single catch rate for estimating past abundance is simpler; (2) the past abundances are between the values obtained using the other methods; and (3) parameter estimates are very similar.

Maximum lifetime reproductive rates are relatively similar among model runs (Table A3.7). For the 1980's, the estimated rates vary from a value of 4.10 to 4.44 spawners per spawner. For the 2000's, they vary from 0.67 to 1.03. The lowest value came from Model 2 (1997 to 2010 data only). All values are low enough that populations would have no capacity to compensate for the effects of environmental perturbations (floods, droughts, years of lower at-sea survival), leading to the conclusion that that this population is expected to extirpate in the absence of human intervention or environmental change.

Further discussion of the parameter values and their implications for recovery planning is provided in the main body of the text (Sections 2.2. and 2.5).

Table A3.1. Recreational catches for the entire St. Mary's River, 1974-2010.

Year	Season	Catch (small)	Retained (small)	Released (small)	Catch (large)	Retained (large)	Released (large)	Effort (rod days)
1974	open	1735	1735	0	217	217	0	n/a
1975	open	238	238	0	73	73	0	n/a
1976	open	1386	1386	0	128	128	0	n/a
1977	open	605	605	0	158	158	0	n/a
1978	open	199	199	0	128	128	0	n/a
1979	open	1521	1521	0	87	87	0	n/a
1980	open	1969	1969	0	201	201	0	n/a
1981	open	1133	1133	0	359	359	0	n/a
1982	open	747	747	0	81	81	0	n/a
1983	open	746	677	69	239	178	61	8703
1984	open	919	721	198	231	66	165	5571
1985	open	1453	1198	255	856	0	856	6896
1986	open	1416	1128	288	945	0	945	7714
1987	open	612	524	88	321	0	321	4241
1988	open	1197	1006	191	578	0	578	6810
1989	open	517	454	63	365	0	365	5334
1990	open	1794	1402	392	238	0	238	5706
1991	open	816	623	193	221	0	221	4725
1992	open	281	250	31	134	0	134	3763
1993	open	905	735	170	395	0	395	6197
1994	open	33	14	19	23	0	23	1268
1995	open	439	318	121	106	0	106	3072
1996	open	553	0	553	164	0	164	976
1997	open	98	0	98	35	0	35	425
1998	open	18	0	18	2	0	2	40
1999	open	4	0	4	1	0	1	19
2000	close	0	0	0	0	0	0	0
2001	open	95	0	95	75	0	75	244
2002	open	38	0	38	13	0	13	194
2003	closed	0	0	0	0	0	0	0
2004	open	39	0	39	21	0	21	105
2005	open	13	0	13	0	0	0	119
2006	open	219	2	217	69	0	69	476
2007	open	208	3	205	89	0	89	597
2008	open	213	0	213	67	0	67	380
2009	open	65	0	65	51	0	51	301
2010	closed	0	0	0	0	0	0	0

Table A3.2. Spawning escapement for large and small salmon, and egg deposition time series used for inputs for the St. Mary's River (West Branch) population dynamics models. Data for the 1997 to 2010 time period are based on the mark-recapture estimates for the West Branch, whereas estimates for the earlier time period are derived from the recreational catch assuming either (1) the annual catch rates = 0.3 (Base Model and Model 3), (2) the annual catch rates equal those estimated for the LaHave River (Appendix 2); or (3) the catch rates equal those estimated for the LaHave River hatchery salmon (Amiro and Jefferson 1998).

	Base Model and Model 3			Model 4			Model 5		
Year:	Small	Large	Eggs	Small	Large	Eggs	Small	Large	Eggs
1974	2,226	278	5,659,077	3,531	441	8,977,965	821	102	2,086,305
1975	305	93	1,095,010	484	148	1,737,202	176	54	632,060
1976	1,779	164	4,186,916	2,822	261	6,642,423	757	70	1,782,713
1977	776	203	2,590,226	1,231	322	4,109,320	838	220	2,797,444
1978	256	164	1,418,226	406	261	2,249,976	516	332	2,863,466
1979	1,951	112	4,196,362	2,285	147	5,009,978	1,853	106	3,984,238
1980	2,527	257	6,088,712	3,313	337	7,979,678	5,979	609	14,404,153
1981	1,454	461	5,316,008	2,300	576	7,521,560	1,329	421	4,860,350
1982	959	103	2,342,557	1,474	239	4,065,279	1,356	146	3,313,045
1983	994	339	3,773,506	3,106	398	7,953,500	1,776	590	6,649,567
1984	1,284	384	4,560,037	1,618	446	5,527,147	1,341	398	4,748,643
1985	1,999	1,551	12,632,329	1,350	1,135	9,042,978	1,168	1,061	8,280,687
1986	1,969	1,712	13,513,175	1,399	1,218	9,612,782	2,911	2,340	18,870,571
1987	832	581	4,886,413	733	626	4,963,359	547	432	3,499,818
1988	1,637	1,047	9,051,517	2,794	1,227	12,197,641	2,251	1,343	11,887,015
1989	697	661	5,103,263	510	727	5,146,308	388	443	3,277,902
1990	2,509	431	7,063,522	2,116	342	5,829,046	1,651	317	4,843,673
1991	1,149	400	4,412,039	1,981	656	7,408,061	1,594	521	5,920,056
1992	377	243	2,093,855	696	288	2,935,093	560	330	2,932,468
1993	1,251	715	6,426,550	1,129	630	5,708,905	809	522	4,501,128
1994	52	42	336,987	191	61	702,765	158	115	957,155
1995	627	192	2,254,563	757	164	2,326,189	593	184	2,145,543
1996	1,002	297	3,544,863	714	189	2,395,017	557	165	1,970,656
1997	390	61	1,063,003	390	61	1,063,003	390	61	1,063,003
1998	1,059	41	2,163,185	1,059	41	2,163,185	1,059	41	2,163,185
1999	307	83	1,039,775	307	83	1,039,775	307	83	1,039,775
2000	315	25	717,745	315	25	717,745	315	25	717,745
2001	319	106	1,195,060	319	106	1,195,060	319	106	1,195,060
2002	220	16	492,808	220	16	492,808	220	16	492,808
2003	600	122	1,798,766	600	122	1,798,766	600	122	1,798,766
2004	464	23	977,021	464	23	977,021	464	23	977,021
2005	192	8	395,480	192	8	395,480	192	8	395,480
2006	222	18	508,050	222	18	508,050	222	18	508,050
2007	182	23	464,345	182	23	464,345	182	23	464,345
2008	361	36	865,206	361	36	865,206	361	36	865,206
2009	96	15	261,573	96	15	261,573	96	15	261,573
2010	123	14	304,856	123	14	304,856	123	14	304,856

Table A3.3. Proportions of St. Mary's River (West Branch) adult Atlantic salmon that are virgin 1SW, virgin 2SW, and repeat spawning salmon based on samples collected during seining from 1998 to 2010. The proportion of 2SW salmon in the large component of the population is also shown.

		Proportion			
Year	Total abundance	1SW	2SW	Repeat spawners	2SW in the large component
1998	1,100	0.95	0.02	0.03	0.42
1999	390	0.74	0.10	0.15	0.40
2000	340	0.91	0.04	0.05	0.47
2001	425	0.72	0.19	0.09	0.68
2002	236	0.87	0.07	0.07	0.50
2003	722	0.86	0.14	0.00	1.00
2004	486	0.92	0.03	0.05	0.40
2005	200	0.92	0.00	0.08	0.00
2006	240	0.95	0.03	0.02	0.60
2007	205	0.86	0.09	0.05	0.64
2008	397	0.91	0.07	0.02	0.80
2009	111	0.88	0.07	0.00	1.00
2010	183	0.84	0.12	0.04	0.75

Table A3.4. Mean fork length and proportion female for small and large Atlantic salmon in the St. Mary's River based on samples collected during fall seining. Fecundity of each size class of female salmon, as well as the expected number of eggs per fish (sexes combined) are also shown.

	Mean fork length (cm)		Proportion female	
Year	Small	Large	Small	Large
1997	53.7	72.5	0.60	0.82
1998	52.3	80.1	0.61	1.00
1999	54.6	75.4	0.67	0.96
2000	52.8	73.5	0.53	1.00
2001	54.5	72.0	0.58	1.00
2002	54.6	76.3	0.64	1.00
2003	53.7	73.4	0.53	0.93
2004	54.5	74.2	0.67	1.00
2005	54.5	61.4	0.58	1.00
2006	52.8	69.3	0.58	0.86
2007	52.5	69.1	0.43	0.87
Averages	53.7	72.5	0.58	0.95
	Eggs per female		Eggs per fish	
	Small	Large	Small	Large
Fecundity	3118	6155	1824	5838

Table A3.5. Smolt abundance in the West Branch of the St. Mary's River from 2005 to 2009, and the number of smolts by age class in the samples collected each year.

Year	Abundance Estimate	Number at Age			
		Age-1	Age-2	Age-3	Age-4
2005	7,350	0	185	44	0
2006	25,100	0	218	17	0
2007	16,110	0	232	21	0
2008	15,217	0	230	21	0
2009	14,820	0	165	5	0

Table A3.6. Annual mean density of juvenile Atlantic salmon by age class on the West Branch of the St. Mary's River as estimated from mark-recapture and single pass electrofishing surveys for the years 1990-2010. Un-standardized values are the annual means as reported in the annual assessments. The standardized values are from a generalized linear model with "site" and "year" as factors to correct for the effects of changes in the sites included in the survey each year. The un-standardized values are used in Model 3, and the standardized values are used for Models 1, 2, 4 and 5. Values marked with asterisks were not included in the model. The high value for the age-0 density in 1993 is an extreme outlier (compare with the age-1 density in 1994) and the values in the late 2000's were influenced by stocking.

	Annual means from assessments				Standardized annual means (standard error)			
Year	N	Age-0	Age-1	Age-2	N	Age-0	Age-1	Age-2
1990	3	4.70	7.80	0.90	3	7.95 (5.28)	8.03 (4.1)	0.75 (0.89)
1991	8	25.80	4.20	0.40	5	41.5 (21.35)	3.2 (1.27)	0.87 (0.8)
1992	11	22.00	5.40	0.90	8	31.22 (12.69)	4.6 (1.44)	1.49 (1.08)
1993	4	143.70*	10.20	0.60	4	120.82* (69.48)	3.98 (1.76)	0.4 (0.41)
1994	7	1.40	2.80	0.20	7	3.24 (1.41)	4.03 (1.35)	0.42 (0.32)
1995	9	16.60	2.61	0.36	4	18.51 (10.64)	2.76 (1.22)	0.58 (0.6)
1996	3	11.15	3.23	0.46	3	12.57 (8.35)	3.15 (1.61)	0.74 (0.88)
1997	8	25.22	10.44	0.80	7	22.61 (9.83)	8.56 (2.86)	0.82 (0.63)
1998	8	23.41	6.88	1.75	8	20.36 (8.28)	5.5 (1.72)	1.54 (1.11)
1999	8	12.37	3.44	1.53	8	10.76 (4.38)	2.75 (0.86)	1.34 (0.97)
2000	8	6.66	4.06	0.32	8	5.79 (2.36)	3.25 (1.01)	0.28 (0.21)
2001	5	5.91	5.43	0.71	5	4.63 (2.38)	5.29 (2.09)	0.74 (0.68)
2002	6	3.92	2.14	0.72	6	2.98 (1.4)	1.78 (0.64)	0.73 (0.61)
2003	6	4.23	5.27	0.48	6	3.22 (1.51)	4.4 (1.59)	0.49 (0.41)
2004	6	3.63	0.63	0.36	6	2.76 (1.3)	0.53 (0.19)	0.37 (0.31)
2005	4	7.72	5.58	0.87	5	5.55 (2.86)	3.43 (1.36)	0.66 (0.6)
2006	6	3.78	0.78	0.43	6	2.91 (1.37)	0.65 (0.24)	0.44 (0.37)
2007	7	4.02	2.51	0.06	8	4.08 (1.66)	2.65 (0.83)	0.1 (0.07)
2008	6	6.15	2.51	0.33	6	3.58 (1.68)	2.28 (0.82)	0.42 (0.35)
2009	8	13.13*	2.01	0.03	9	10.35* (3.97)	1.72 (0.51)	0.02 (0.01)
2010	7	6.93*	8.27*	0.17	7	3.93* (1.71)	5.75* (1.92)	0.08 (0.07)

Table A3.7. Maximum likelihood estimates (standard errors) for life history parameter estimates for the St. Mary's River (West Branch) Atlantic salmon population obtained from five versions of the dynamics model. The OFV for Model 2 is not comparable with the values for the other models because the data series are all shorter.

Model	Base	Model 2	Model 3	Model 4	Model 5
Assumptions:					
Time period	1974-2010	1997-2010	1974-2010	1974-2010	1974-2010
Standardized electrofishing data	yes	yes	no	yes	yes
Exploitation rate assumed for past abundances	0.3	0.3	n/a	LaHave model	LaHave hatchery
OFV:	529.1	547.9	223.4	527.3	516.2
Freshwater production:					
M_{Egg}	0.92 (0.01)	0.92 (0.01)	0.91 (0.01)	0.92 (0.01)	0.92 (0.01)
α	0.67 (0.10)	0.59 (0.08)	0.69 (0.11)	0.68 (0.10)	0.65 (0.10)
R_{asy}	11.76 (2.52)	infinite	14.98 (4.31)	11.05 (2.16)	11.79 (2.57)
M_{Parr}	0.34 (0.10)	0.40 (0.09)	0.45 (0.08)	0.34 (0.10)	0.34 (0.10)
j_2	0.85 (0.02)	0.86 (0.02)	0.84 (0.02)	0.85 (0.02)	0.85 (0.02)
Egg to smolt dynamics:					
$\tilde{\alpha}$	0.03 (0.01)	0.02 (<0.01)	0.03 (0.01)	0.03 (0.01)	0.03 (0.01)
$\tilde{R}_{asy}$	104,120 (29,861)	infinite	108,260 (38,475)	98,248 (26,482)	105,110 (30,421)
Return Rates (%):					
1SW average (1980-1989)	3.33 (0.63)	n/a	3.43 (0.71)	3.58 (0.70)	3.16 (0.62)
1SW average (2000-2009)	1.18 (0.17)	1.23 (0.19)	1.22 (0.18)	1.19 (0.17)	1.18 (0.17)
2SW average (1980-1989)	0.74 (0.14)	n/a	0.76 (0.16)	0.66 (0.13)	0.70 (0.14)
2SW average (2000-2009)	0.09 (0.01)	0.09 (0.01)	0.09 (0.01)	0.09 (0.01)	0.09 (0.01)
Lifetime egg production per smolt:					
average EPS (1980-1989)	132.07 (25.20)	n/a	135.76 (28.07)	133.21 (26.03)	125.24 (24.85)
average EPS (2000-2009)	30.46 (4.47)	31.46 (4.80)	31.33 (4.67)	30.62 (4.49)	30.46 (4.47)
Max. lifetime reproductive rate:					
average (1980-1989)	4.44 (0.87)	n/a	4.10 (0.95)	4.43 (0.92)	4.23 (0.89)
average (2000-2009)	1.02 (0.13)	0.67 (0.07)	0.95 (0.13)	1.02 (0.13)	1.03 (0.13)
Equilibrium egg abundance:					
average (1980-1989)	10,651,000 (1,176,900)	n/a	11,111,000 (1,612,500)	10,133,000 (735,020)	10,049,000 (912,320)
average (2000-2009)	71,262 (375,670)	0	0	54,218 (357,100)	87,130 (376,070)
Equilibrium smolt abundance:					
average (1980-1989)	80,646 (19,612)	n/a	81,843 (24,002)	76,069 (17,089)	80,235 (19,173)
average (2000-2009)	2,339 (12,316)	0	0	1,770 (11,648)	2,860 (12,324)

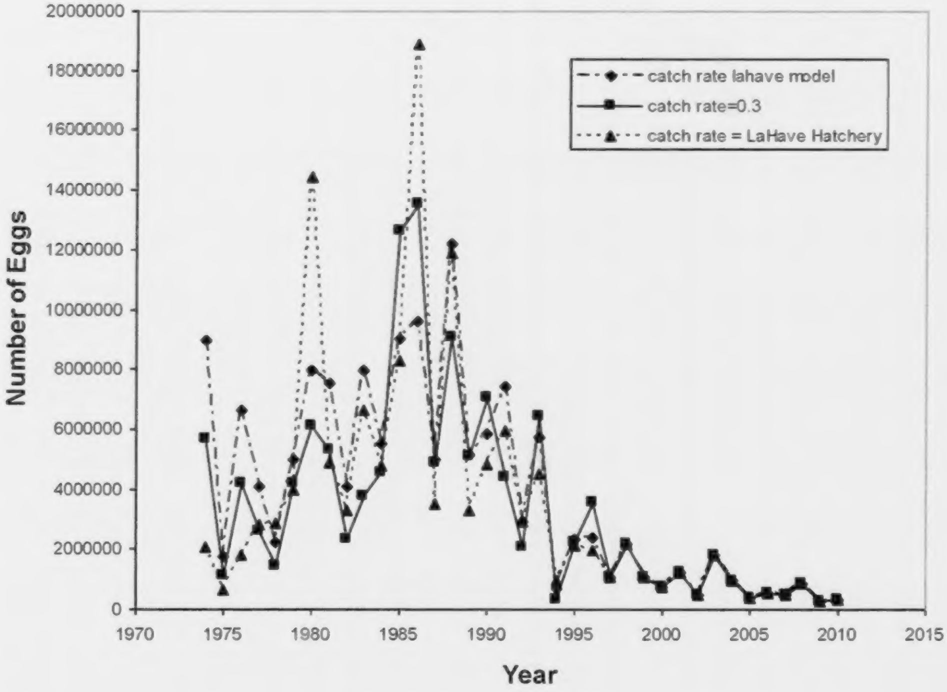

Figure A3.1. A comparison of the egg deposition time series for the St. Mary's River (West Branch) Atlantic salmon populations derived based on three assumptions about the catch rate in the recreational fishery used to extrapolate past abundance: (1) that the rate equals 0.3 (base model – O'Neil et al. (1997b)); (2) that the rate equals the rate for 1SW hatchery salmon on the LaHave River (as suggested as a potential method in O'Neil et al. (1998);, and (3) that the rate equals the catch rate estimated for the Lahave River Atlantic salmon population, as estimated in Appendix 2. Egg depositions are the same for the three series from 1997 to present and are those estimated by seining and mark-recapture.

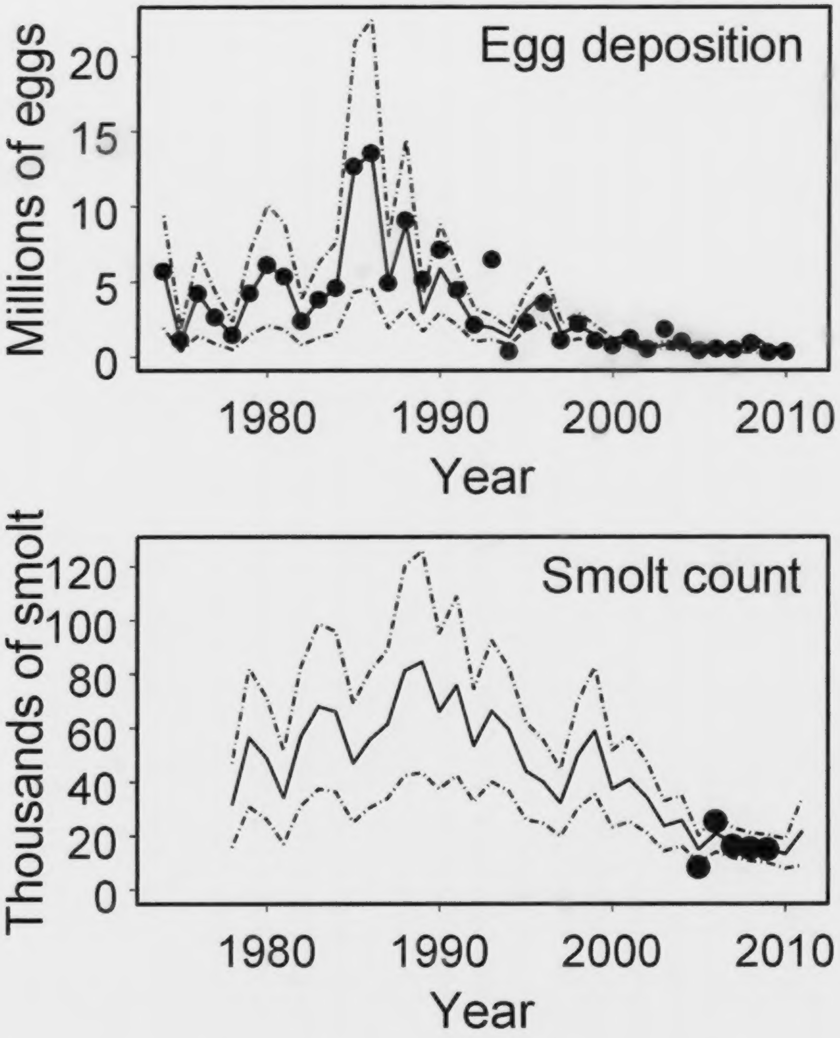

Figure A3.2. Observed (points) and estimated (solid lines) egg depositions (top panel) and smolt counts (bottom panel) from the base population dynamics model run for the St. Mary's River (West Branch) Atlantic salmon population. The dashed lines show 95% confidence intervals based on normal approximations.

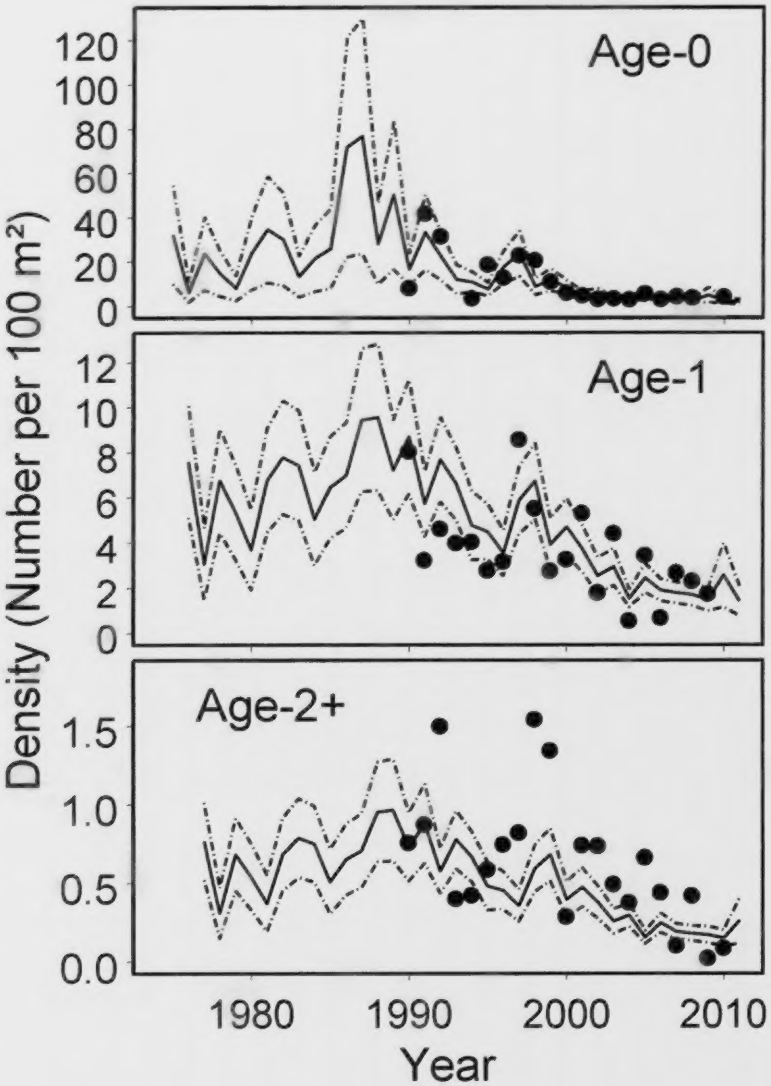

Figure A3.3. Observed (points) and estimated (solid lines) age-0 (top panel), age-1 (middle panel) and age-2+ (bottom panel) juvenile salmon densities from the base population dynamics model run for the St. Mary's River (West Branch) Atlantic salmon population. The dashed lines show 95% confidence intervals based on normal approximations.

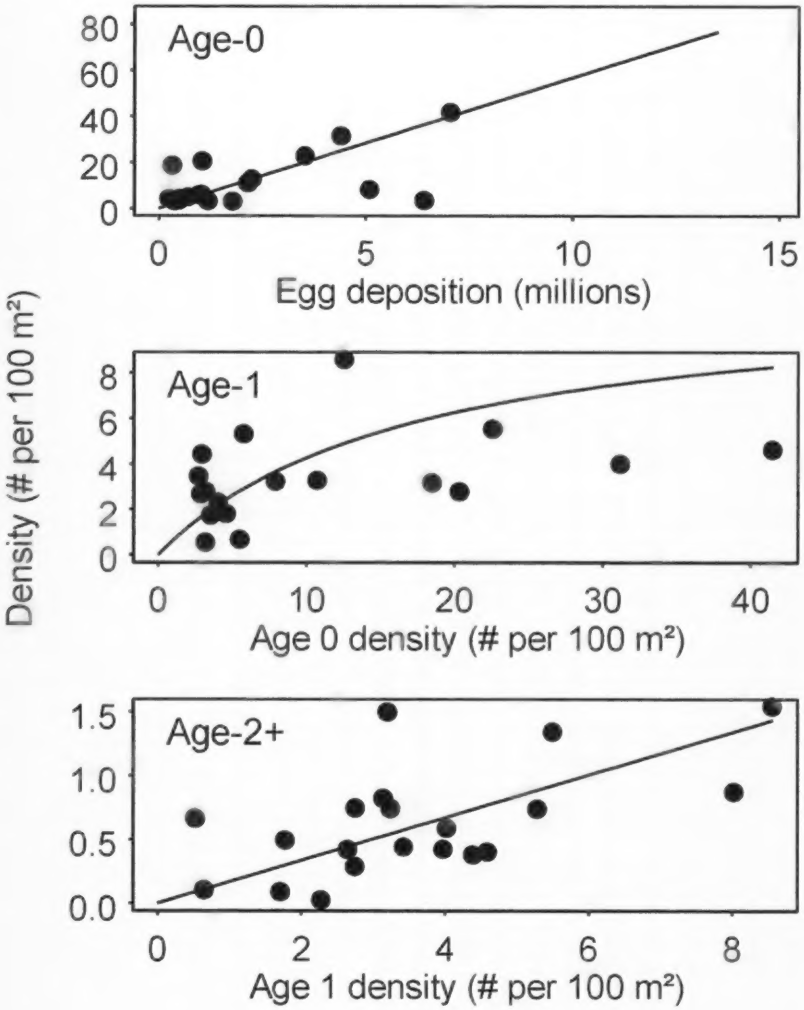

Figure A3.4. Functional relationships between the abundance of eggs, and the densities of age-0, age-1 and age-2+ juvenile Atlantic salmon from the base population dynamics model run for the St. Mary's River (West Branch) Atlantic salmon population. The points show the data and the lines show the fitted relationships between age classes.

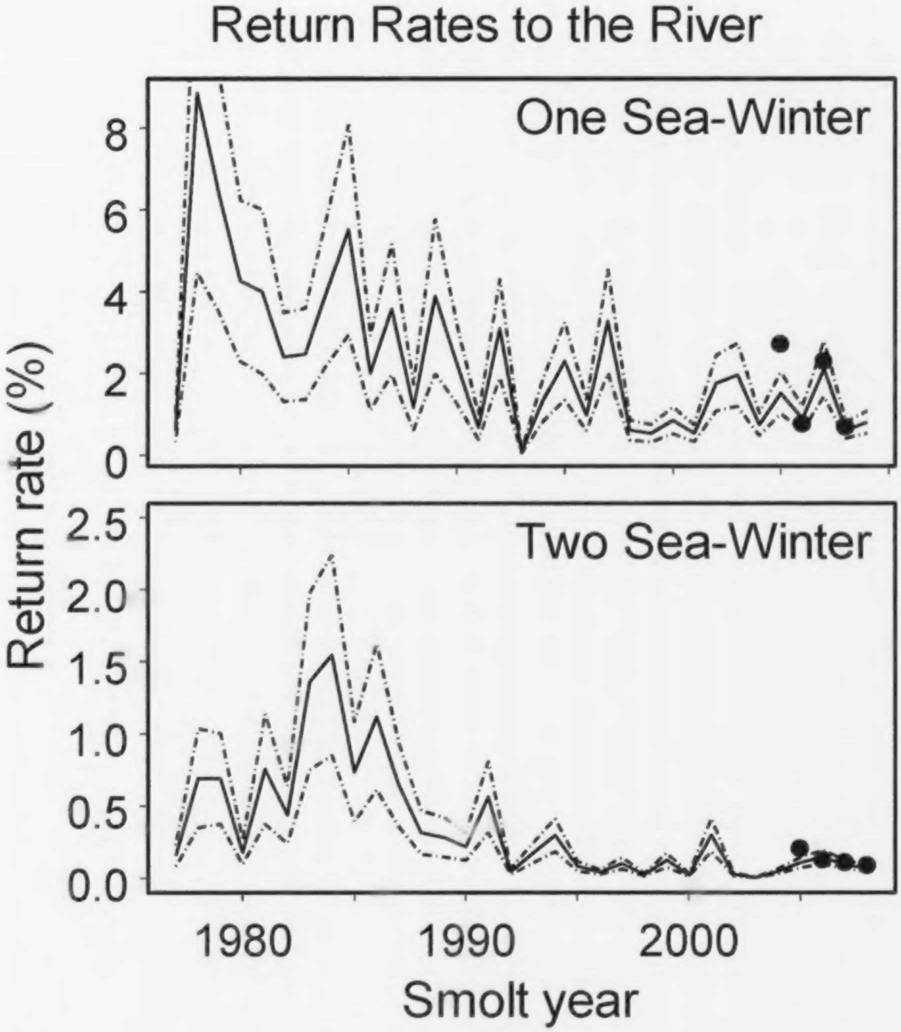

Figure A3.5. Observed (points) and estimated (solid lines) smolt-to-adult return rates to the river mouth (indicative of at-sea survival) for salmon returning as 1SW (top panel) and 2SW (bottom panel) adults. Estimates are obtained from the base population dynamics model run for the St. Mary's River (West Branch) Atlantic salmon population. The dashed lines show 95% confidence intervals based on normal approximations.

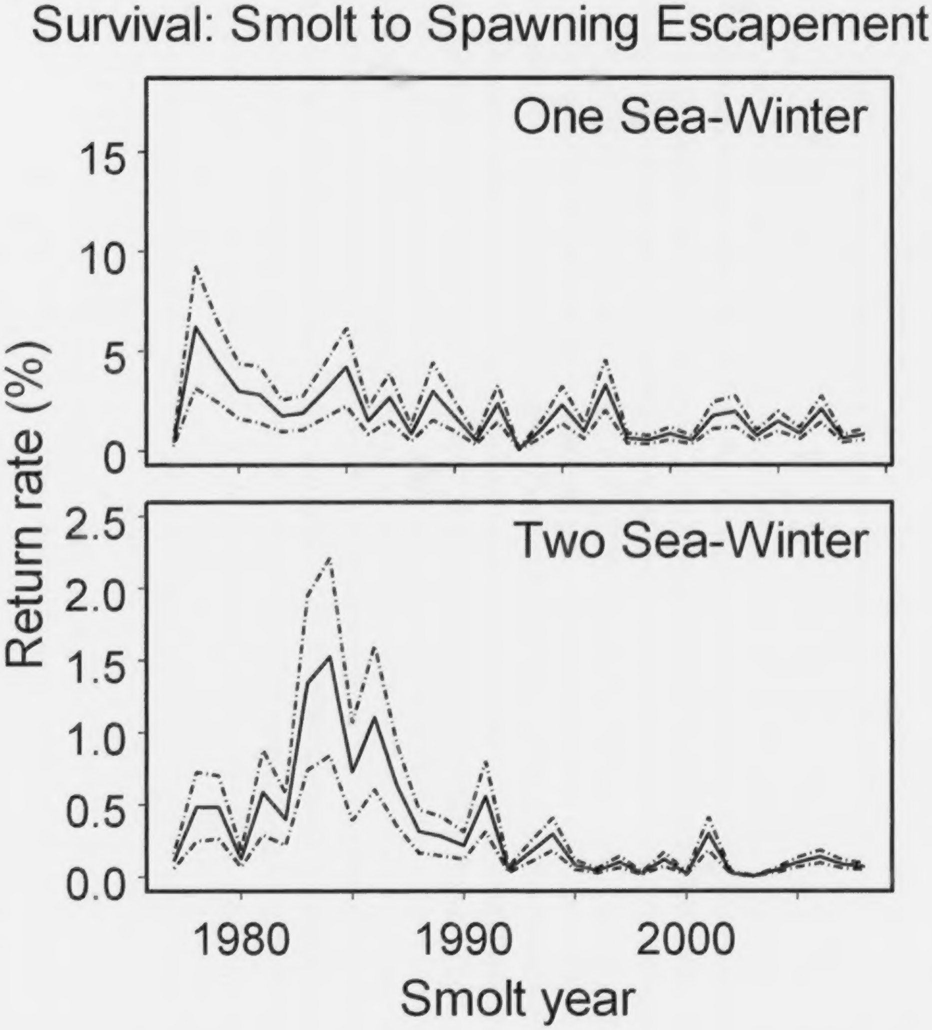

Figure A3.6. Estimated (solid lines) smolt-to adult return rates to spawning escapement (includes the effects of both at-sea survival and the recreational fishery) for salmon returning as 1SW (top panel) and 2SW (bottom panel) adults. Estimates are obtained from the base population dynamics model run for the St. Mary's River (West Branch) Atlantic salmon population. The dashed lines show 95% confidence intervals based on normal approximations.

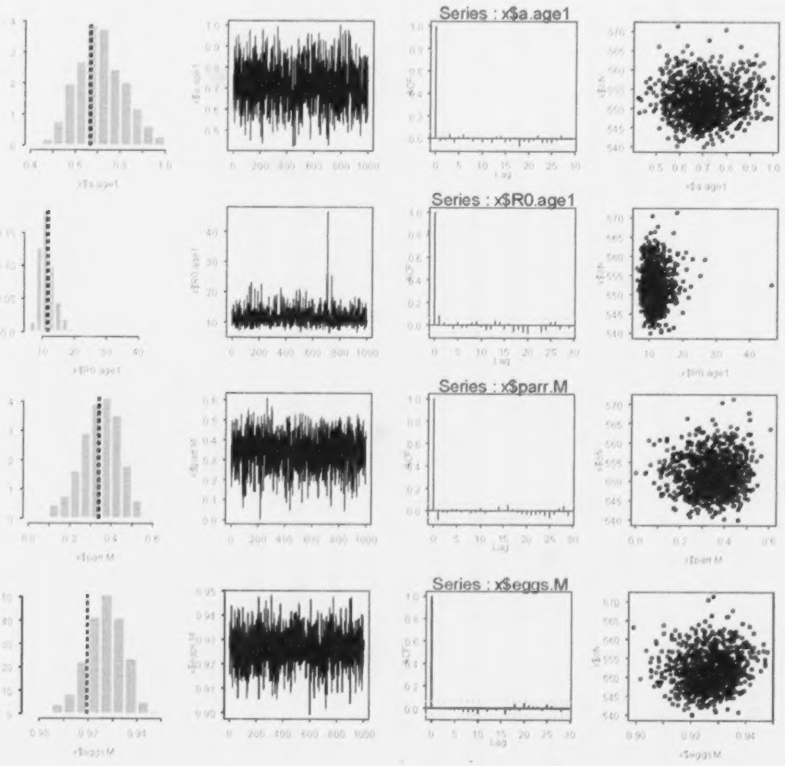

Figure A3.7. MCMC results for the freshwater production model survival parameters for the St. Mary's River (West Branch) base model run. The first column shows the probability density (the dashed lines are the maximum likelihood estimates), the second column shows the thinned chain, the third column shows the autocorrelation in the chain, and the fourth column is a plot of the objective function value versus the parameter value for each step in the MCMC chain.

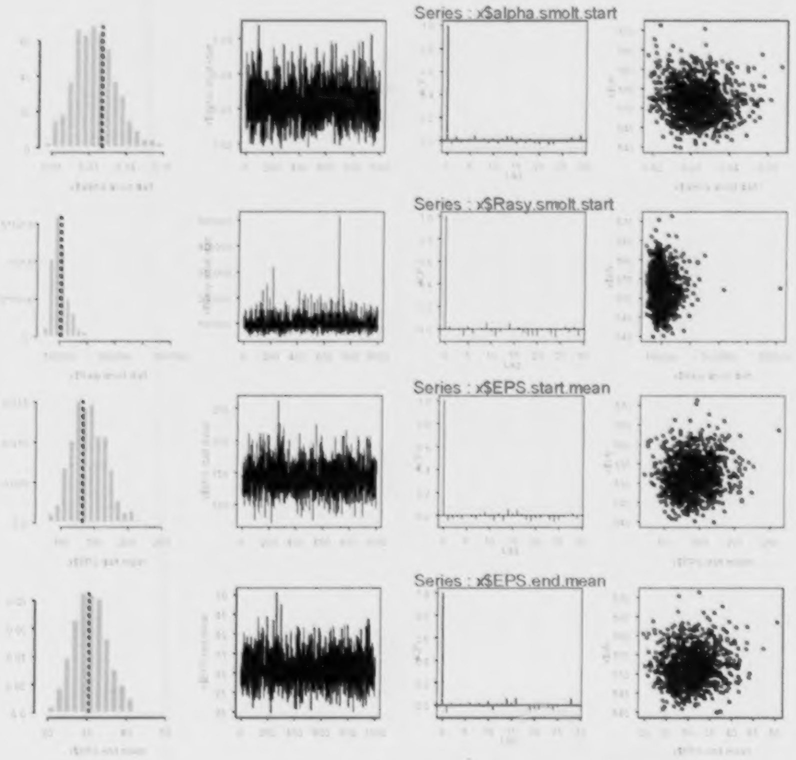

Figure A3.8. MCMC results for four derived model parameters for the St. Mary's River (West Branch) base model run: the egg-to-smolt Beverton-Holt alpha and asymptotic recruitment level and the mean lifetime EPS values for the 1980's and 2000's time periods. The first column shows the probability density (the dashed lines are the maximum likelihood estimates), the second column shows the thinned chain, the third column shows the autocorrelation in the chain, and the fourth column is a plot of the objective function value versus the parameter value for each step in the MCMC chain.

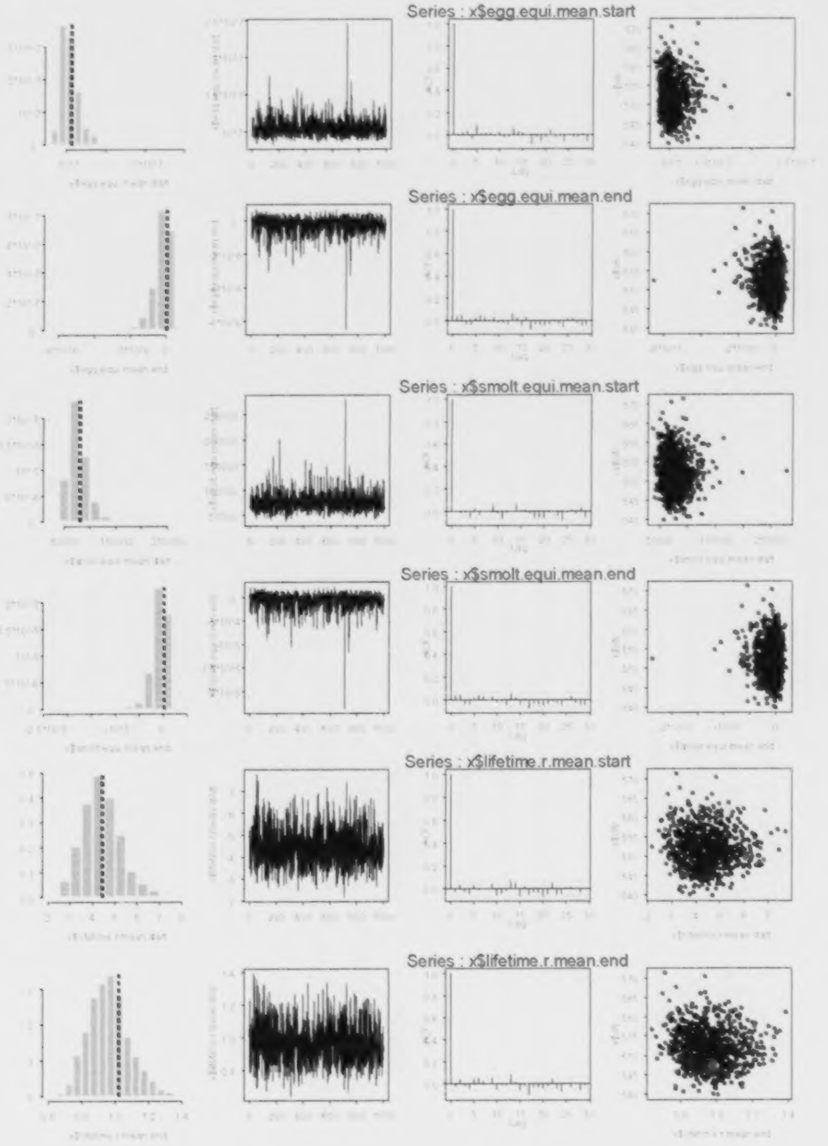

Figure A3.9. MCMC results for three derived model parameters (mean equilibrium abundance of eggs, mean equilibrium abundance of smolts, and maximum lifetime reproductive rate) for two time periods (start = 1980's; end = 2000's) for the St. Mary's River (West Branch) base model. The first column shows the probability density (the dashed lines are the maximum likelihood estimates), the second column shows the thinned chain, the third column shows the autocorrelation in the chain, and the fourth column is a plot of the objective function value versus the parameter value for each step in the MCMC chain.

APPENDIX 4. DESCRIPTION OF MODELS USED FOR THE POPULATION VIABILITY ANALYSES FOR SOUTHERN UPLAND ATLANTIC SALMON

The PVAs presented in Sections 4 and 5 were carried out using a forward projecting population model developed specifically for the life history of Southern Upland Atlantic salmon. PVA is a powerful tool to explore current conditions, assess risks and simulate how future management actions or environmental changes could influence the abundance of a population (Reed et al. 2002).The dynamical model (i.e. describing the life history) is a variation to the one described in Appendix 1. The main differences in the models are: (1) the PVA is a two-sex model; and (2) all repeat spawning salmon are assumed to be consecutive year spawners after their second spawning (they may be alternate or consecutive year spawners between their first and second spawning). This second change has very little effect on the model output because it only slightly modifies the probability of surviving between spawning events and very, very few salmon survive to spawn a third time.

Two sets of life history parameter values are used in the simulations: those representative of the 1980's (past dynamics) and those representative of the 2000's (present dynamics). These values are those estimated using the statistical model and are provided in Section 2. The notation used in the model is provided in Table 4.1 and the model equations are provided in Table 4.2.

The dynamical equations are used to project the population forward from a starting abundance equal to the estimated adult population size in 2010. For both the past and present scenarios the numbers of eggs, parr, smolt and adults, as well as their age, sex and previous spawning structure, are calculated using the mean life history parameter values specific to the simulation.

Random variability was incorporated into future mortality rates, sex ratio, and smoltification schedules for greater biological realism (Shelton et al. 2007). A lognormal distribution was used for the deviates around the mortality parameters (or functions), and a normal distribution was used for the probabilities of smoltification, the probability of being a consecutive or alternate year repeat spawner and for the sex ratio parameters, after a logistic transformation. Lognormal distributions are often used to model the deviates around survival functions as survival is multiplicative in nature (Hilborn and Walters 1992). Given that sex ratio and maturity are proportions, the logistic transformation is appropriate given the binomial nature of their error distributions.

Deviates are expected to be temporally autocorrelated (Hilborn 2001), given that the effect of environmental variability on population vital rates tends not to be completely random (Lande et al. 2003). As the strength of this autocorrelation increases, good years are increasingly likely to be followed by good years (and bad followed by bad).

Example of how lognormal variability in survival parameters was incorporated:

Let $\overline{M}$ equal the average instantaneous rate of mortality affecting a life stage of salmon (as estimated using the life history model), σ_w equal the standard deviation of the residuals of the mortality rate (the amount of variability in the rate) and d be a constant describing the degree of autocorrelation. The instantaneous mortality used in the forward projection in year t is given by:

$$M_t = \overline{M} + w_t + \sigma_w^2 / 2$$

where

$$w_t = (w*_{t-1} d + w*_t)\sigma_w$$

and

$$w^*_t \sim N(0,1) .$$

The parameter M_t is then used to model the survival between two ages, following the general format of:

$$N_{t+1} = N_t \exp(-M_t)$$

Note that although the annual proportion surviving as estimated by this algorithm is not strictly bounded to fall below one, for practical purposes it meets this criterion given the rates used in this analysis. In multiple model runs of 2000 simulated populations each with several life history parameters, at no time was a survival value greater than one simulated with this algorithm.

For the population projection model used in the PVA (above), the random variability in the egg, parr and mature salmon mortality parameters M_t^{Egg}, M_t^{Parr}, M_t^{Mat} were modeled in this fashion, after converting the annual mortality rates estimated with the statistical model to instantaneous rates . Additionally, the return rates for 1SW and 2SW salmon were converted to instantaneous mortality rates and modeled similarly, and random variability was included around the age-0 to age-1 survival function in the same way.

Example of how logistic variability was incorporated into stage transition probabilities and sex ratios:

Let p be the mean parameter value in the form of a proportion. The logit of the mean of the parameter (ρ) becomes:

$$\rho = \ln(p/(1-p))$$

Autocorrelated random deviates for t years are calculated as:

$$w_t = (w^*_{t-1} d + w^*_t)\sigma_w$$

where

$$w^*_t \sim N(0,1),$$

where d and σ_w are as described above.

The annual probability becomes:

$$p_t = \exp(\rho + w_t)/(1+\exp(\rho + w_t)),$$

where p_t is the probability of transitioning from one life stage to another (e.g. smolting at a given age), or sex ratio in the given year.

Random variability and autocorrelation:

Where possible, the amount of random variability and strength of auto-correlation were derived from the statistical life-history model output. Time series models were used to evaluate autocorrelation in the annual estimates of 1SW and 2SW return rates (Section 2: Figures 2.2.4 and 2.2.5). Autocorrelation was estimated at time lags of zero to 15 years for each series (converted to instantaneous rates) for both the LaHave River (above Morgans Falls) and St. Mary's (West Branch) populations. Autocorrelation was detected most consistently at a time lag of one (Figure A4.1). A first-order ARIMA model was then fit to the time series to estimate the autocorrelation coefficients and residual variances (Table A4.3). Based on this analysis, the autocorrelation coefficient in the marine environment was set to 0.45, and a (instantaneous) return rate variance of 0.475 was used for the PVAs for both populations.

Annual estimates are not available for the other model parameters, so values for autocorrelation and the amount of random variability were assumed. The same autocorrelation coefficient value was assumed for the freshwater environment as was derived for the marine environment. However, random variability was assumed to be lower in the freshwater environment and values of $\sigma = 0.2$ were assumed for all other model parameters, except for the probability of smoltification for which a value of 0.3 was assumed. Within limits, the general extinction patterns are not overly sensitive to perturbations of the variances (i.e. higher or lower values for σ), although the time to extinction does vary as more or less variability is assumed. Examples of a simulated mortality rate and smoltification probability time series are shown for the LaHave River (above Morgans Falls) PVAs for the past and present in Figures A2.2 and A2.3 to illustrate how mortality varies in the PVA. Note that, because the same random numbers are used to generate the series, the pattern is the same for each parameter, but the values are re-scaled by the average rates.

Catastrophic events:
Atlantic salmon occupy naturally variable habitats that are at times subject to extreme conditions. Floods and droughts in fresh water are examples of these, both of which can lead to very high mortality in one or many of the juvenile life stages. The effects of extreme events are included in the model using two parameters. The first parameter is the frequency parameter, ψ, which is the expected frequency of these events in a given number of years. A random number, υ_t, is drawn from a uniform distribution [0,1] for each year in each simulated population trajectory, and the value $1/\psi$ is compared to υ_t. If $1/\psi < \upsilon$, that year is considered an extreme event year. The second parameter, ϑ, is used to model the effect of the event. In this analysis, the effect of the event was included between the egg and the fry life stages, thereby allowing density-dependent compensation to occur which would partially offset some of the mortality (because the survival of age-0 to age-1 increases as population size decreases). The effect of the extreme events would be greater if it was incorporated after density dependence. The simulated number of fry, $P_{t,0}$, is then:

$$P_{t+1,0} = \left\langle \begin{array}{ll} Egg_t e^{-M_t^{Egg}} \vartheta & \text{if } 1/\psi < \upsilon_t,\ \ \upsilon_t \sim \text{unif}[0,1] \\ Egg_t e^{-M_t^{Egg}} & \text{otherwise} \end{array} \right\rangle .$$

In the absence of specific information about the frequency and effects of extreme events, values of 10 and 0.2 were assumed for ψ and ϑ, respectively. This means that on average, 10 events reducing the abundance of fry by 80% from the expected value would occur every 100 years. As modeled, a greater or lesser number of extreme events could occur in any simulated population trajectory, and their distribution through time is random. To illustrate the effects of including extreme events, 1000 random survival values were generated assuming a mean survival of 0.5 and $\sigma = 0.2$. These values are compared to a set of random survivals including catastrophic events assuming values of 10 and 0.2 for ψ and ϑ, respectively (Figure A4.4). In this example, the median survival is reduced from 0.488 to 0.476 when extreme events are included.

Probability of extinction and recovery:
For each scenario analyzed with the PVA, 2000 population trajectories were simulated and the extinction probabilities are calculated as the proportion of populations that go extinct by a

specified time. A quasi-extinction threshold of 15 females is assumed and an egg deposition of zero is assigned if the abundance drops below this value. A population must be below this value for two consecutive years to be assumed extinct in a given year. If the female abundance is higher the next year, the egg deposition is calculated as per the model. A population can therefore sit on the quasi-extinction for a number of years and can theoretically recover. Recovery probabilities were calculated as the proportion of the simulated population trajectories that were above the recovery target in a given year. As such, a population could be in a recovered state for a period of time, and then cease to be considered recovered if its abundance subsequently declined to a level below the recovery target.

In instances where comparisons were made between scenarios, the same set of random numbers was used to generate variability in parameter values to ensure that the differences between the scenarios do not occur by chance (i.e. because a different set of numbers is used).

Table A4.1. Parameters and indices used in the population viability analyses for the St. Mary's River (West Branch) and LaHave River (above Morgans Falls) Atlantic salmon populations.

Model parameter	Description
t	Year
a	Total age
c	Number of years as an immature salmon at sea
ps	Number of previous spawning events
s	Sex (F = female, M = male)
i	Repeat spawning strategy (1= consecutive year repeat spawner, 2=alternate year repeat spawner)
Egg_t	Egg deposition in year t
$P_{t,a}$	Abundance of parr of age a in year t
$S_{t,a}$	Abundance of smolt of age a in year t
$Esc_{t,a,c,ps,s}$	Spawning escapement in year t of salmon of age a, of sex s, that spent c years at sea as an immature salmon, and that have spawned ps times previously
M_t^{Egg}	Instantaneous mortality rate in year t from egg to fry
ϑ	Survival reduction for years with extreme mortality events
ψ	Inverse of the probability that a year has an extreme mortality event
α	Maximum survival from age-0 to age-1 (slope at the origin of the Beverton-Holt model)
R_{asy}	Asymptotic age-1 density (N/100 m^2)
h	Electrofishing scalar (habitat area in m^2)
ε_t	Age-0 to age-1 survival deviate in year t
j_t^a	Probability of smolting at age a in year t
M_t^{Parr}	Instantaneous mortality rate in year t of parr age-1 and older
δ	Multiplier used to for changing freshwater productivity in recovery scenarios
RR_t^c	Return rate of salmon in category c in year t
v_t^c	Sex ratio of first time spawning salmon in category c in year t
p_t^{alt}	Probability in year t that a salmon is an alternate-year repeat spawner
M_t^{mat}	Instantaneous mortality rate in year t of mature (post-spawning) salmon

Table A4.2. Model equations for the population viability analyses for the St. Mary's River (West Branch) and LaHave River (above Morgans Falls) Atlantic salmon populations. Notation is provided in Table A4.1.

	Description	Equation
1	Annual egg depositions	$Egg_t = \sum_{t,a,c,ps} Esc_{t,a,c,ps,\mathrm{F}} f_{c,ps}$
2	Abundance of fry (age-0)	$P_{t+1,0} = \begin{Bmatrix} Egg_t e^{-M_t^{Egg}} \vartheta & \text{if } 1/\psi < \upsilon_t, \ \ \upsilon_t \sim \text{unif}\,[0,1] \\ Egg_t e^{-M_t^{Egg}} & \text{otherwise} \end{Bmatrix}$
3	Abundance of age-1 parr (incorporating density dependence)	$P_{t+1,1} = \dfrac{\alpha P_{t,0}}{1 + \dfrac{\alpha P_{t,0}}{R_{asy} h}} (1 - j_t^1) \exp(\varepsilon_t)$
4	Abundance of age-2 and older parr	$P_{t+1,a+1} = P_{t,a} \exp(\text{-}M_t^{Parr})(1 - j_t^a)$
5	Abundance of smolt of age a	$S_{t+1,a+1} = \begin{Bmatrix} \dfrac{\alpha P_{t,a}}{1 + \dfrac{\alpha P_{t,a}}{R_{asy} h}} \exp(\varepsilon_t) j_t^{a+1} \delta & a = 0 \\ P_{t,a} \exp(\text{-}M_t^{Parr})(j_t^{a+1}) \delta & a = 1,2,3 \end{Bmatrix}$
6	Abundance of 1st time spawning male and female salmon of total age a and sea age c	$Esc_{t+c,a+c,c,0,s} = \begin{Bmatrix} S_{t,a} RR_t^c v_t^c & s = \mathrm{F} \\ S_{t,a} RR_t^c (1 - v_t^c) & s = \mathrm{M} \end{Bmatrix}$
7	Abundance of salmon spawning for a second time	$Esc_{t+i,a+i,c,1,s} = \begin{Bmatrix} Esc_{t,a,c,0,s} (1 - p_t^{alt}) \exp(-M_t^{mat}) & i = 1 \\ Esc_{t,a,c,0,s} (p_t^{alt}) \exp(-(M_t^{mat} + M_{t+1}^{mat})) & i = 2 \end{Bmatrix}$
8	Abundance of salmon spawning for a third time or more	$Esc_{t+1,a+1,c,ps+1,s} = Esc_{t,a,c,ps,s} \exp(-M_t^{mat}) \quad ps \geq 2$

Table A4.3. First-order autocorrelation and log-scale residual variance in the return rate time series for 1SW and 2SW Atlantic salmon in the St. Mary's River (West Branch) and LaHave River (above Morgans Falls).

	Autocorrelation coefficient		Log scale variance	
	1SW	2SW	1SW	2SW
LaHave	0.453	0.546	0.442	0.491
St. Mary's	0.332	0.441	0.347	0.591
Averages:	0.393	0.493	0.395	0.541

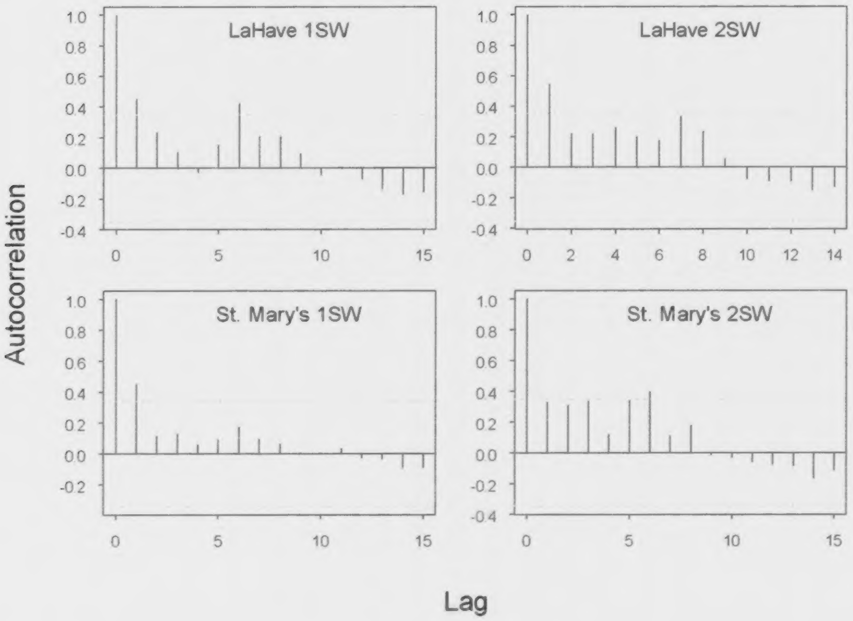

Figure A4.1. Autocorrelation coefficients in the return rate time series for 1SW (left panels) and 2SW (right panels) Atlantic salmon in the LaHave River above Morgans Falls (top panels) and the West Branch of the St. Mary's River (bottom panels) at lags of zero to 15 years. The dashed lines indicate statistical significance at a 95% confidence level.

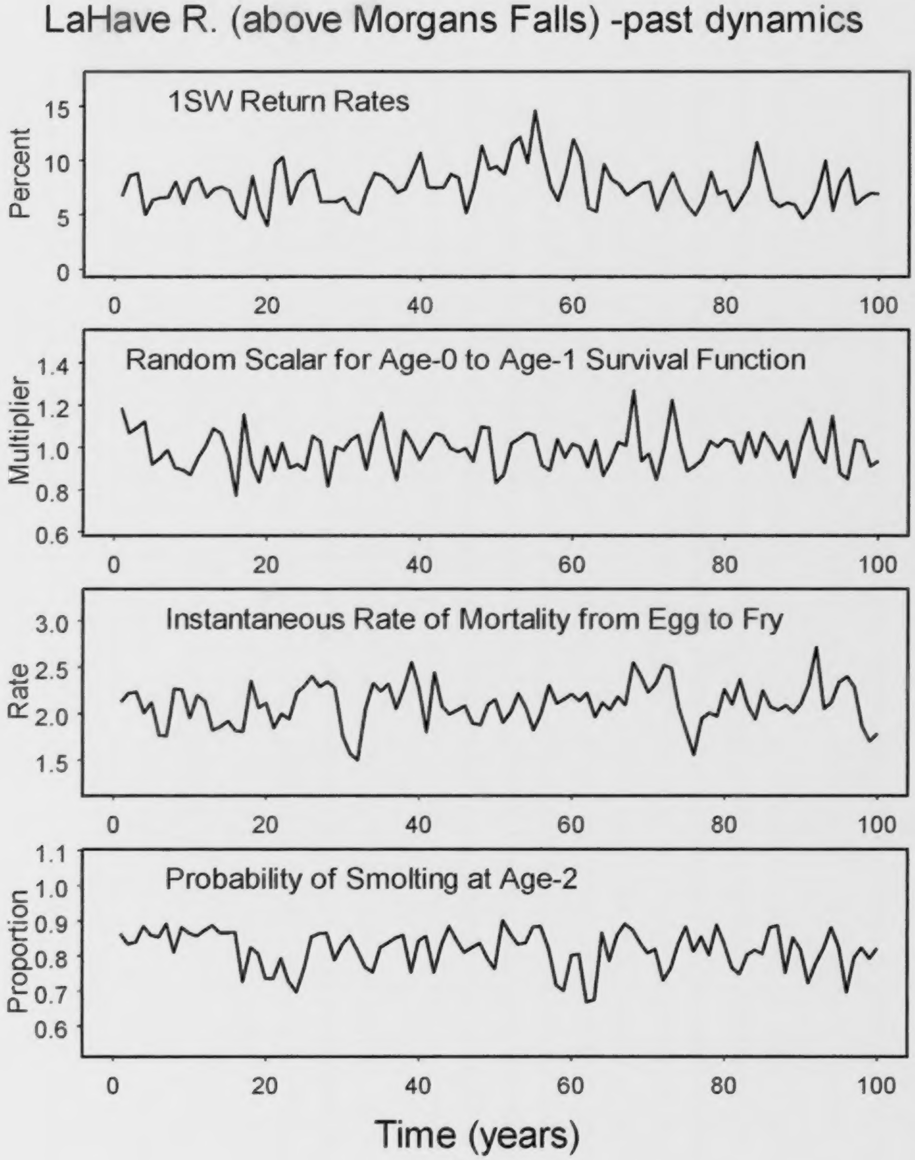

Figure A4.2. Examples of how the life history parameter values used change through time given the autocorrelation values and extent of random variability used in the analyses. Starting values for the parameters are from the base case population viability analysis for LaHave River (above Morgans Falls) using past (1980's) population dynamics. Values are for a single 100-year stochastic projection.

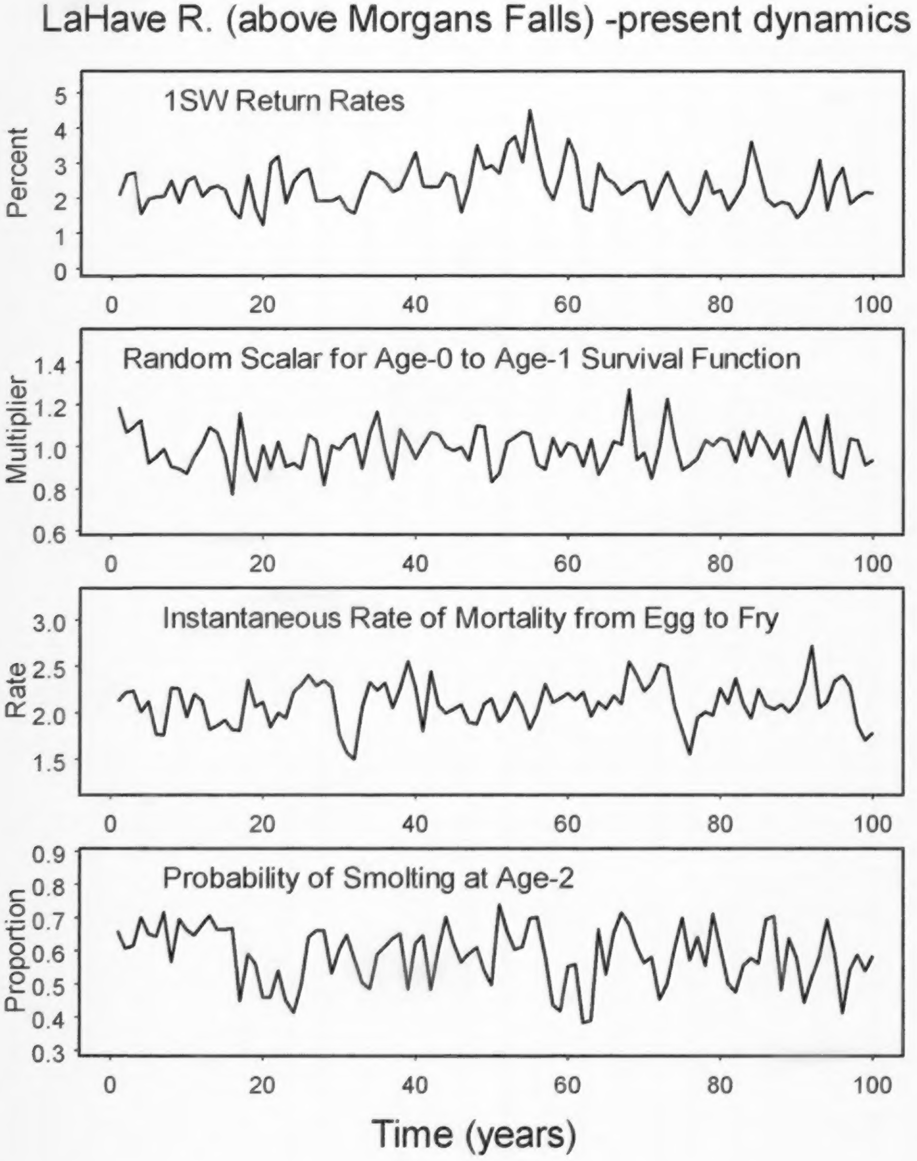

Figure A4.3. Examples of how the life history parameter values used change through time given the autocorrelation values and extent of random variability used in the analyses. Starting values for the parameters are from the base case population viability analysis for LaHave River (above Morgans Falls) using present (2000's) population dynamics. Values are for a single 100-year stochastic projection.

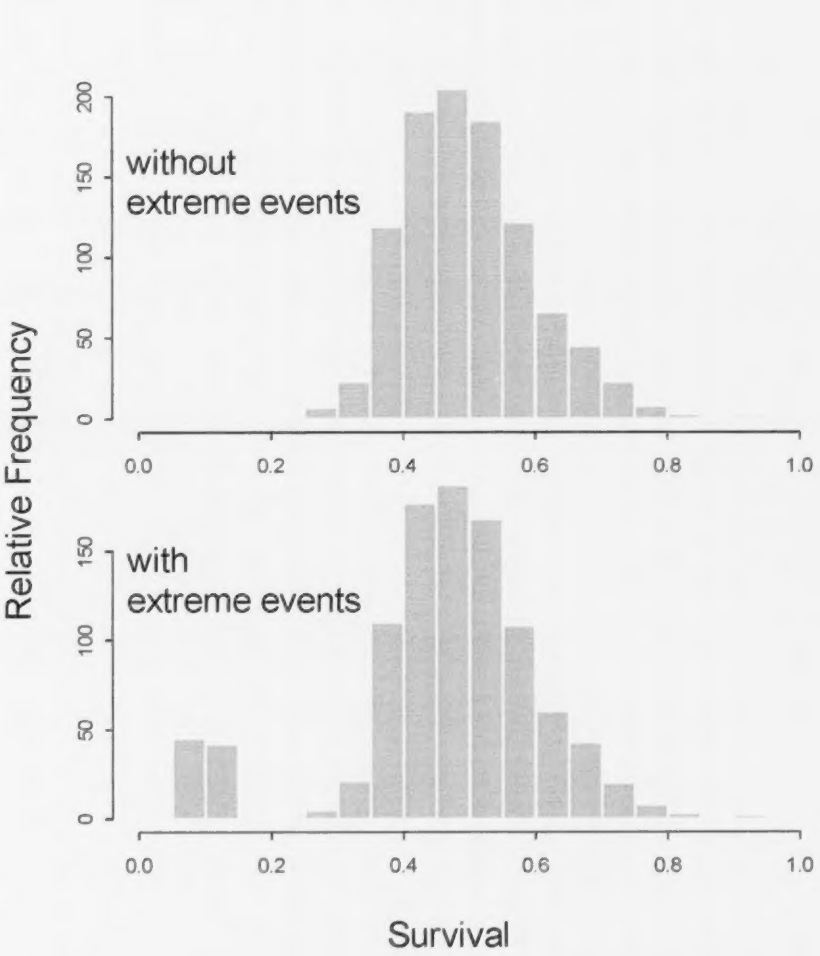

Figure A4.4. Comparison of two sets of 1000 random survival values generated assuming a mean survival of 0.5 and $\sigma = 0.2$ *with the distribution in the lower panel including catastrophic events. Values of 10 and 0.2 were assumed for* ψ *and* ϑ*, respectively.*